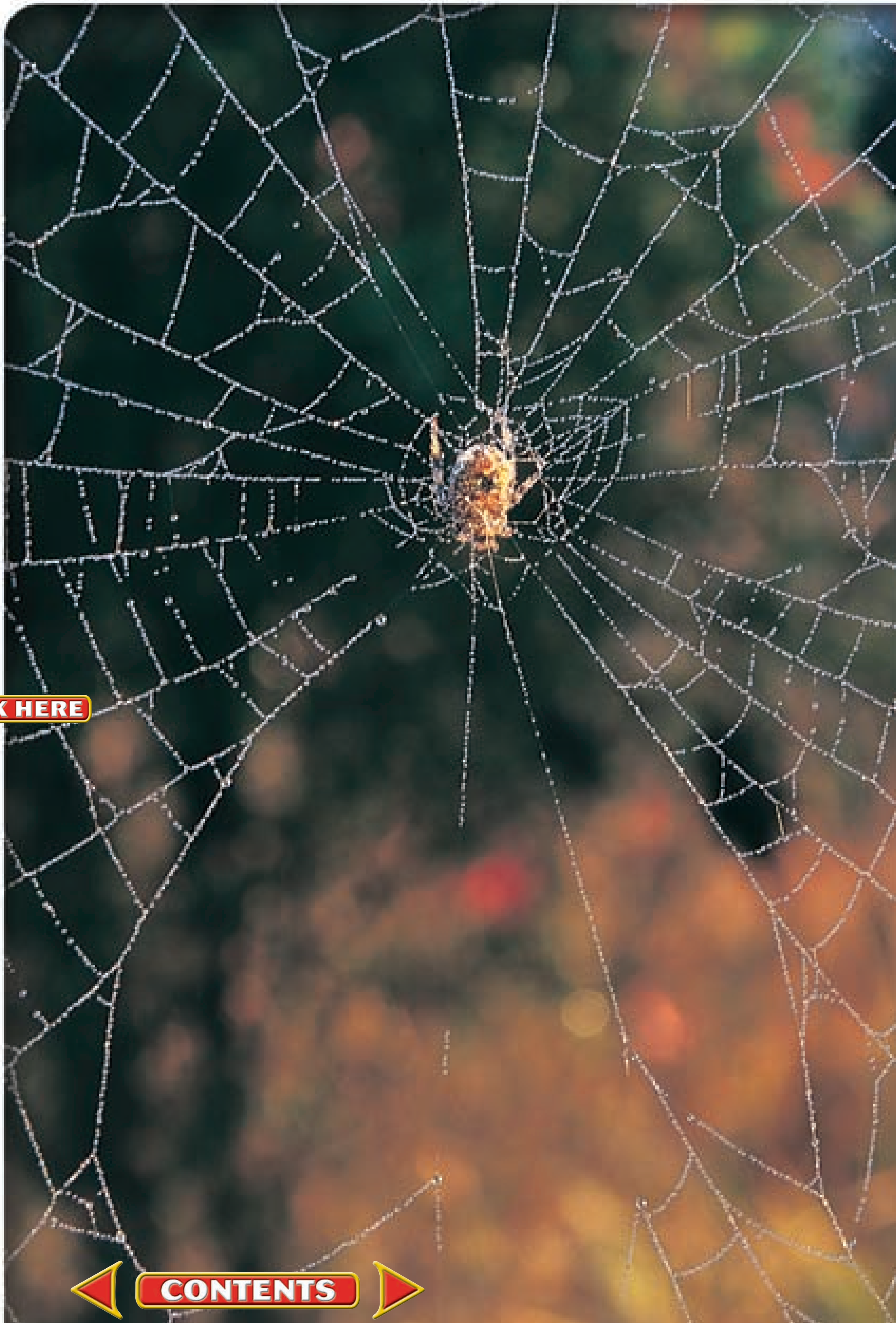
CHAPTER 24

The Chemistry of Life



What You'll Learn

- You will learn the functions of the four major classes of biological molecules: proteins, carbohydrates, lipids, and nucleic acids.
- You will identify the building blocks that form the major biological molecules.
- You will compare and contrast the metabolic processes of cellular respiration, photosynthesis, and fermentation.

Why It's Important

The large biological molecules in your body are essential to the organization and operation of its millions of cells. The structure of these molecules is directly related to their function, and how they function affects your health and survival.

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CHEMISTRY Online

Visit the Chemistry Web site at **science.glencoe.com** to find links about the chemistry of life.

The silk that makes up this spider's web is, gram for gram, stronger than steel, yet it is lightweight and stretchable. Spider silk is made of protein, a biological molecule.

DISCOVERY LAB

Materials

400-mL beaker
hot plate
10-mL graduated cylinder
boiling chip
10% glucose solution
test tube
tongs
Benedict's solution
stirring rod
other food solutions such as 10% starch or honey

Testing for Simple Sugars

Your body constantly uses energy. Many different food sources can supply that energy, which is stored in the bonds of molecules called simple sugars. What foods contain simple sugars?

Safety Precautions

Procedure

1. Fill a 400-mL beaker one-third full of water. Place this water bath on a hot plate and begin to heat it to boiling.
2. Place 5.0 mL 10% glucose solution in a test tube.
3. Add 3.0 mL Benedict's solution to the test tube. Mix the two solutions using a stirring rod. Add a boiling chip to the test tube.
4. Using tongs, place the test tube in the boiling water bath and heat for five minutes.
5. Record a color change from blue to yellow or orange as a positive test for a simple sugar.
6. Repeat the procedure using food samples such as a 10% starch solution, a 10% gelatin (protein) suspension, or a few drops of honey suspended in water.

Analysis

Was a color change observed? Which foods tested positive for the presence of a simple sugar?

Section 24.1 Proteins

Objectives

- **Describe** the structures of amino acids and proteins.
- **Explain** the roles of proteins in cells.

Vocabulary

protein
amino acid
peptide bond
peptide
denaturation
enzyme
substrate
active site

An amazing variety of chemical reactions take place in living organisms. At the forefront of coordinating the numerous and intricate reactions of life are the large molecules called proteins, whose name comes from the Greek root word *protos*, meaning first.

Protein Structure

You have learned that polymers are large molecules made of many repeating building blocks called monomers. **Proteins** are organic polymers made of amino acids linked together in a specific way. But proteins are not just large, randomly arranged chains of amino acids. To function properly, each protein must be folded into a specific three-dimensional structure. The spider silk shown on the opposite page would not be the incredibly strong yet lightweight protein that it is if it were not constructed in its specific way. You will learn in this section how proteins are made from their amino-acid building blocks and how different types of proteins function.

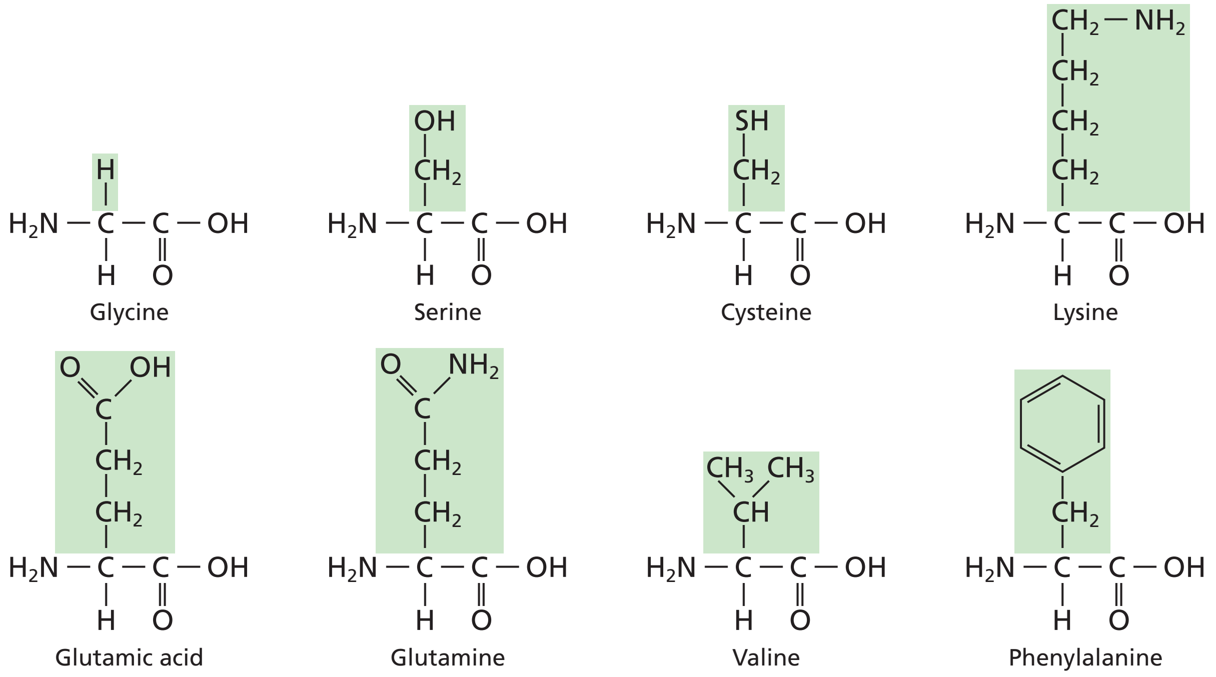
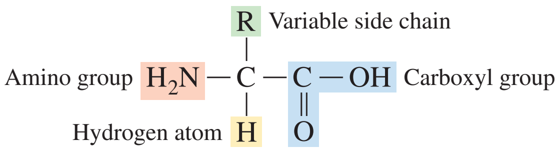


Figure 24-1

A large variety of side chains can be found on amino acids. Some of them are shown on these representative amino acids and are highlighted in green.

Amino acids As you saw in Chapter 23, many different functional groups are found in organic compounds. **Amino acids**, as their name implies, are organic molecules that have both an amino group and an acidic carboxyl group. The general structure of an amino acid is shown below.



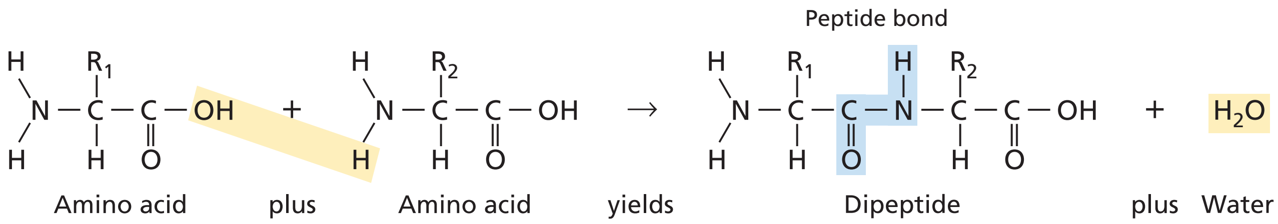
Each amino acid has a central carbon atom around which are arranged four groups: an amino group (— NH_2), a carboxyl group (— COOH), a hydrogen atom, and a variable side chain, *R*. The side chains range from a single hydrogen atom to a complex double-ring structure. Examine the different side chains of the amino acids shown in **Figure 24-1**. Identify the nonpolar alkanes, polar hydroxyl groups, acidic and basic groups such as carboxyl and amino groups, aromatic rings, and sulfur-containing groups. This wide range of side chains gives the different amino acids a large variety of chemical and physical properties and is an important reason why proteins can carry out so many different functions.

Twenty different amino acids are commonly found in the proteins of living things. The name of each amino acid and its three-letter abbreviation are listed in **Table 24-1**. What is the abbreviation for glycine?

Figure 24-2

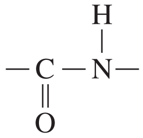
The amino group of one amino acid bonds to the carboxyl group of another amino acid to form a dipeptide. The organic functional group formed is an amide linkage and is called a peptide bond.

The peptide bond The amino and carboxyl groups provide convenient bonding sites for linking amino acids together. Since an amino acid is both an amine and a carboxylic acid, two amino acids can combine to form an



amide, releasing water in the process. This reaction is a condensation reaction. As **Figure 24-2** shows, the amino group of one amino acid reacts with the carboxyl group of another amino acid to form an amide functional group. Where do the H and OH that form water come from?

The amide bond that joins two amino acids is referred to by biochemists as a **peptide bond**.



Peptide bond

A molecule that consists of two amino acids bound together by a peptide bond is called a dipeptide. **Figure 24-3a** shows the structure of a dipeptide that is formed from the amino acids glycine (Gly) and phenylalanine (Phe). **Figure 24-3b** shows a different dipeptide, also formed by linking together glycine and phenylalanine. Is Gly-Phe the same compound as Phe-Gly? No, they're different. Examine these two dipeptides to see that the order in which amino acids are linked in a dipeptide is important.

Each end of the two-amino-acid unit in a dipeptide still has a free group—one end has a free amino group and the other end has a free carboxyl group. Each of those groups can be linked to the opposite end of yet another amino acid, forming more peptide bonds. A chain of two or more amino acids linked together by peptide bonds is called a **peptide**. Living cells always build peptides by adding amino acids to the carboxyl end of a growing chain.

Polypeptides As peptide chains increase in length, other ways of referring to them become necessary. A chain of ten or more amino acids joined by peptide bonds is referred to as a polypeptide. When a chain reaches a length of about 50 amino acids, it's called a protein.

Because there are only 20 different amino acids that form proteins, it might seem reasonable to think that only a limited number of different protein structures are possible. But a protein can have from 50 to a thousand or more amino acids, arranged in any possible sequence. To calculate the number of possible sequences these amino acids can have, you need to consider that each position on the chain can have any of 20 possible amino acids. For a peptide that contains n amino acids, there are 20^n possible sequences of the amino acids. So a dipeptide, with only two amino acids, can have 20^2, or 400, different possible amino acid sequences. Even the smallest protein containing only 50 amino acids has 20^{50}, or more than 1×10^{65}, possible arrangements of amino acids! It is estimated that human cells make between 80 000 and 100 000 different proteins. You can see that this is only a very small fraction of the total number of proteins possible.

Table 24-1

The 20 Amino Acids

Amino acid	Abbreviation
Alanine	Ala
Arginine	Arg
Asparagine	Asn
Aspartic acid	Asp
Cysteine	Cys
Glutamic acid	Glu
Glutamine	Gln
Glycine	Gly
Histidine	His
Isoleucine	Ile
Leucine	Leu
Lysine	Lys
Methionine	Met
Phenylalanine	Phe
Proline	Pro
Serine	Ser
Threonine	Thr
Tryptophan	Trp
Tyrosine	Tyr
Valine	Val

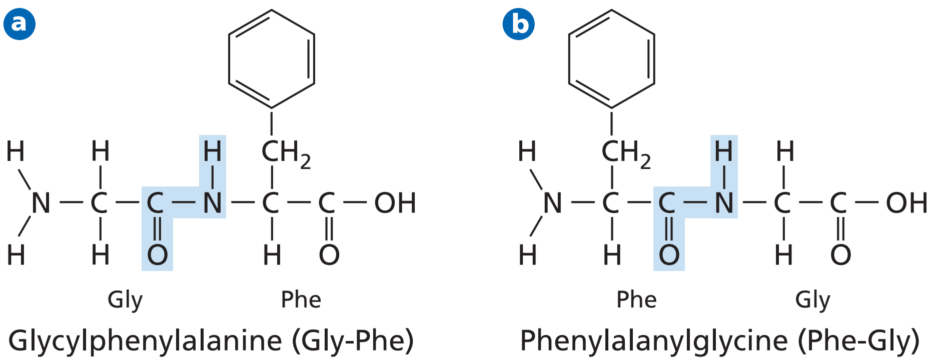


Figure 24-3

a Glycine and phenylalanine can be combined in this configuration.
b Glycine and phenylalanine can also be combined in this configuration. Why are these two structures different substances?

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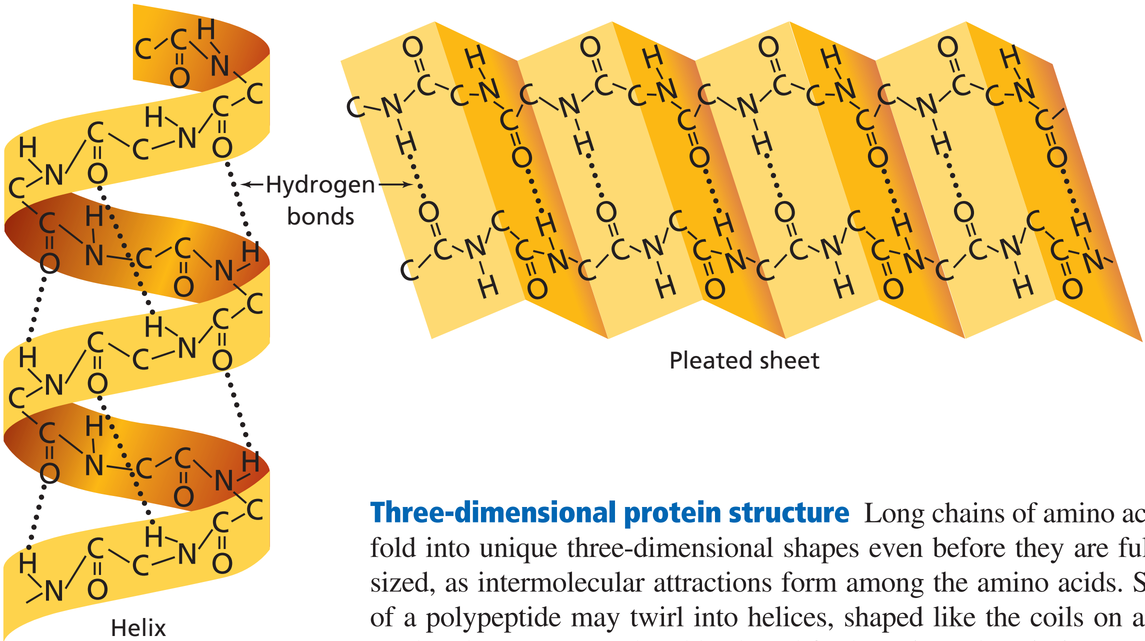


Figure 24-4

The folding of polypeptide chains into both helices (left) and sheets (right) involves amino acids that are fairly close together in the chain being held in position by hydrogen bonds. Other interactions among the various side chains are not shown here but play an important role in determining the three-dimensional shape of a polypeptide.

Three-dimensional protein structure Long chains of amino acids start to fold into unique three-dimensional shapes even before they are fully synthesized, as intermolecular attractions form among the amino acids. Some areas of a polypeptide may twirl into helices, shaped like the coils on a telephone cord. Other areas may bend back and forth again and again into a sheet structure, like the folds of an accordion. A polypeptide chain may also turn back on itself and change direction. A given protein may have several helices, sheets, and turns, or none at all. **Figure 24-4** shows the folding patterns of a typical helix and a sheet. The overall three-dimensional shape of many proteins is globular, or shaped like an irregular sphere. Other proteins have a long fibrous shape. The three-dimensional shape is determined by the interactions among the amino acids.

Changes in temperature, ionic strength, pH, and other factors can act to disrupt these interactions, resulting in the unfolding and uncoiling of a protein. **Denaturation** is the process in which a protein's natural three-dimensional structure is disrupted. Cooking often denatures the proteins in foods. When an egg is hard-boiled, the protein-rich egg white solidifies due to the denaturation of its protein. Because proteins function properly only when folded, denatured proteins generally are inactive.

The Many Functions of Proteins

Proteins play many roles in living cells. They are involved in catalyzing reactions, transporting substances, regulating cellular processes, forming structures, digesting foods, recycling wastes, and even serving as an energy source when other sources are scarce. See the **Everyday Chemistry** feature at the end of this chapter to learn how proteins play a role in the sense of smell.

CHEMISTRY CD-ROM

Go to the **Chemistry Interactive CD-ROM** to find additional resources for this chapter.

Enzymes In most organisms, the largest number of different proteins function as enzymes, catalyzing the many reactions that go on in living cells. An **enzyme** is a biological catalyst. Recall that a catalyst speeds up a chemical reaction without being consumed in the reaction. A catalyst usually lowers the activation energy of a reaction by stabilizing the transition state.

How do enzymes function? The term **substrate** is used to refer to a reactant in an enzyme-catalyzed reaction. Substrates bind to specific sites on enzyme molecules, usually pockets or crevices. The pocket to which the substrates bind is called the **active site** of the enzyme. After the substrates bind to the active site, the active site changes shape slightly to fit more tightly around the substrates. This recognition process is called induced fit. In the diagram in **Figure 24-5**, you'll see that the shapes of the substrates must fit

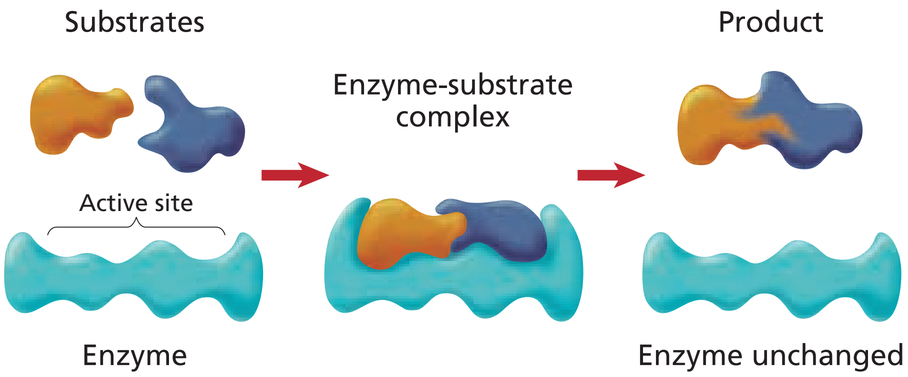


Figure 24-5

Substrates are brought close together as they fit into the uniquely shaped active site of an enzyme. The enzyme then changes shape as it "molds itself" to the substrates, forming an enzyme-substrate complex. Bonds are broken and new bonds form to produce the product in the reaction.

that of the active site, in the same way that puzzle pieces or a lock and key fit together. A molecule only slightly different in shape from an enzyme's normal substrate doesn't bind as well to the active site or undergo the catalyzed reaction.

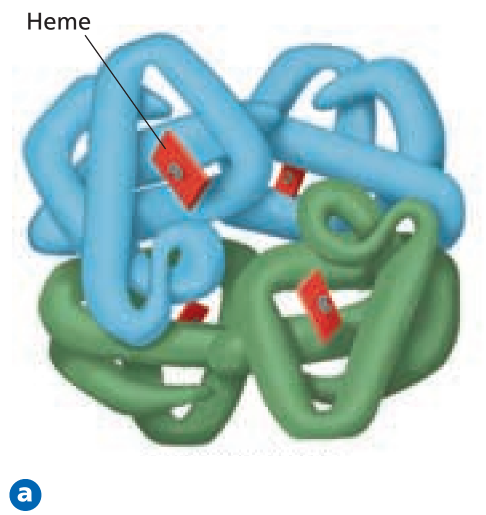
The structure that forms when substrates are bound to an enzyme is called an enzyme-substrate complex. The large size of enzyme molecules allows them to form multiple bonds with their substrates, and the large variety of amino acid side chains in the enzyme allows a number of different intermolecular forces to form. These intermolecular forces lower the activation energy needed for the reaction in which bonds are broken and the substrates are converted to product.

An example of an enzyme you may have used is papain, found in papayas, pineapple, and other plant sources. This enzyme catalyzes a reaction that breaks down protein molecules into free amino acids. Papain is the active ingredient in many meat tenderizers. When you sprinkle the dried form of papain on moist meat, you activate the papain so that it breaks down the tough protein fibers in the meat, making the meat more tender.

Transport proteins Some proteins are involved in transporting smaller molecules throughout the body. The protein hemoglobin, modeled in **Figure 24-6**, carries oxygen in the blood, from your lungs to the rest of your body. Other proteins combine with biological molecules called lipids to transport them from one part of your body to another through the bloodstream. You will learn about lipids later in this chapter.

Figure 24-6

a Hemoglobin is a globular protein with four polypeptide chains. The red structure in each chain is heme, an organic group containing an iron ion to which oxygen binds.
b The pink skin of this pig is due to the hemoglobin in its blood.



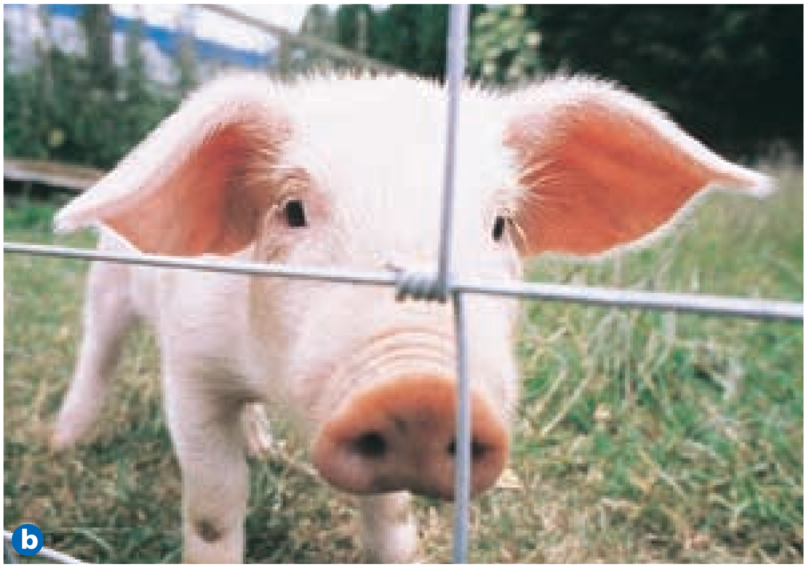
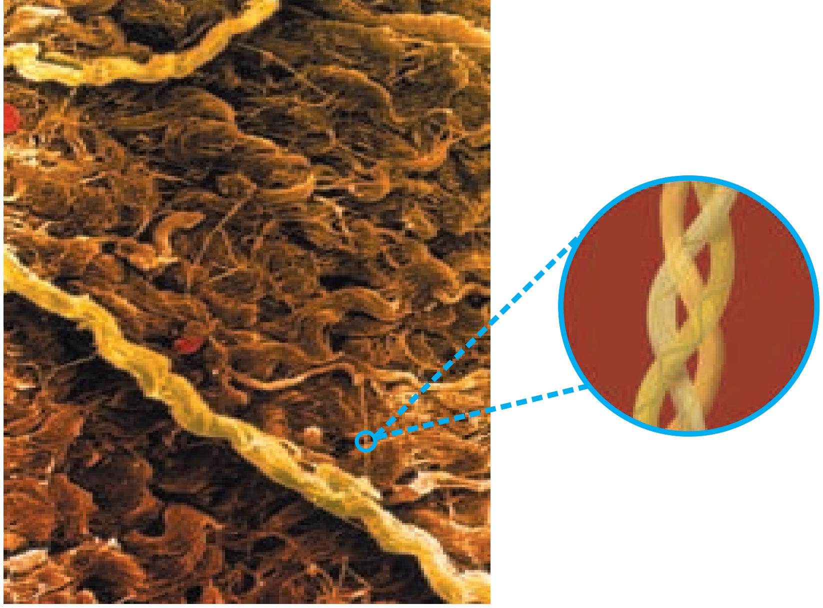


Figure 24-7

Collagen is a fibrous protein that consists of three helical polypeptides (right) that are coiled around one another to form the strong fibers of connective tissue (left). The large ropelike structures in the photo are bundles of collagen fibers, held together by cross-linkage. Collagen is an extremely large protein. Each of the three strands is about 1000 amino acids long.



Structural proteins The sole function of some proteins is to form structures vital to organisms. These molecules are known as structural proteins. The most abundant strutural protein in most animals is collagen, which is part of skin, ligaments, tendons, and bones. **Figure 24-7** shows the structure of collagen. Other structural proteins make up hair, fur, wool, hooves, fingernails, cocoons, and feathers.

Hormones Hormones are messenger molecules that carry signals from one part of the body to another. Some hormones are proteins. Insulin, a familiar example, is a small (51 amino acids) protein hormone made by cells in the pancreas. When insulin is released into the bloodstream, it signals body cells that blood sugar is abundant and should be stored. A lack of insulin results in diabetes, a disease in which there is too much sugar in the bloodstream. Another protein hormone, chorionic gonadotropin, is synthesized by a developing embryo. Release of this hormone causes the development of a placenta that nourishes the embryo.

Because modern technology has made possible the laboratory synthesis of proteins, some protein hormones are being synthetically produced for use as medicines. Insulin, thyroid hormones, and growth hormones are some examples. Both natural and synthetic proteins are used in a variety of products—from meat tenderizer to cleaning solutions to health and beauty aids.

Section 24.1 Assessment

1. Compare the structures of amino acids, dipeptides, polypeptides, and proteins. Which has the largest molecular mass? The smallest?
2. Draw the structure of the dipeptide Gly-Ser, circling the peptide bond.
3. List four functions that different proteins have in living organisms.
4. **Thinking Critically** How do the properties of proteins make them such useful catalysts? How do they differ from other catalysts you have studied?
5. **Applying Concepts** Identify an amino acid from **Figure 24-1** that can be classified into each of the categories in the following pairs.
   - **a.** nonpolar versus polar
   - **b.** aromatic versus aliphatic
   - **c.** acidic versus basic

Carbohydrates

Analyzing the term *carbohydrate* offers a hint about the structure of this group of molecules. Early observations that these compounds have the general chemical formula $C_n(H_2O)_n$ and appear to be hydrates of carbon led to their being called carbohydrates. Although it is now known that there are no full water molecules attached to carbohydrates, the name has stayed.

Objectives

- **Describe** the structures of monosaccharides, disaccharides, and polysaccharides.
- **Explain** the functions of carbohydrates in living things.

Vocabulary

carbohydrate
monosaccharide
disaccharide
polysaccharide

Kinds of Carbohydrates

Why do marathon runners eat large quantities of pasta before a big race? Pasta, as well as milk, fruit, bread, and potatoes, is rich in carbohydrates. The main function of carbohydrates in living organisms is as a source of energy, both immediate and stored. **Carbohydrates** are compounds that contain multiple hydroxyl groups (— OH) as well as a carbonyl functional group (C=O). These molecules range in size from single monomers to polymers made of hundreds or thousands of monomer units.

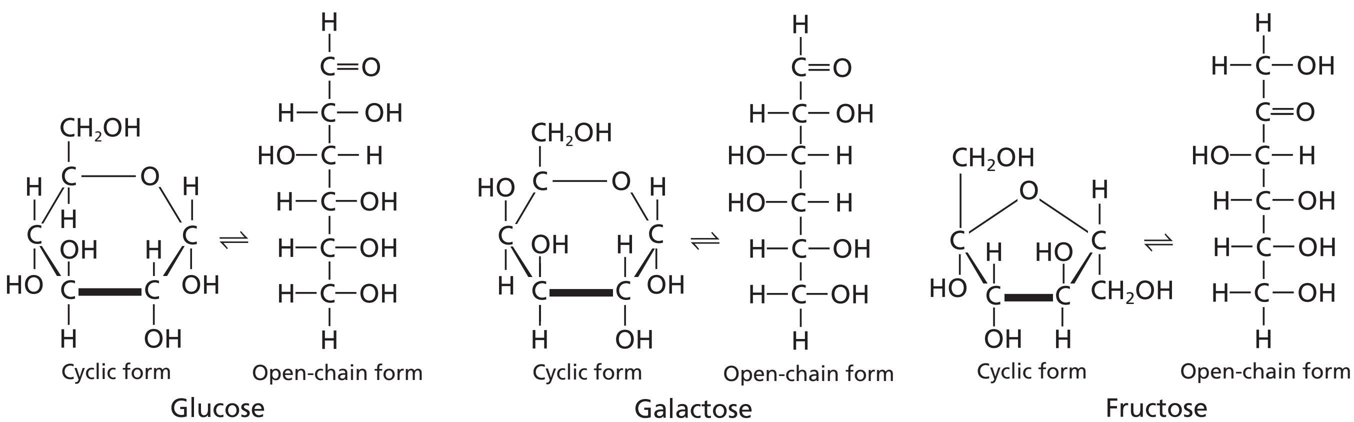
Monosaccharides The simplest carbohydrates, often called simple sugars, are **monosaccharides**. The most common monosaccharides have either five or six carbon atoms. They have a carbonyl group on one carbon and hydroxyl groups on most of the other carbons. The presence of a carbonyl group makes these compounds either aldehydes or ketones, depending upon the location of the carbonyl group. Multiple polar groups make monosaccharides water soluble and give them high melting points.

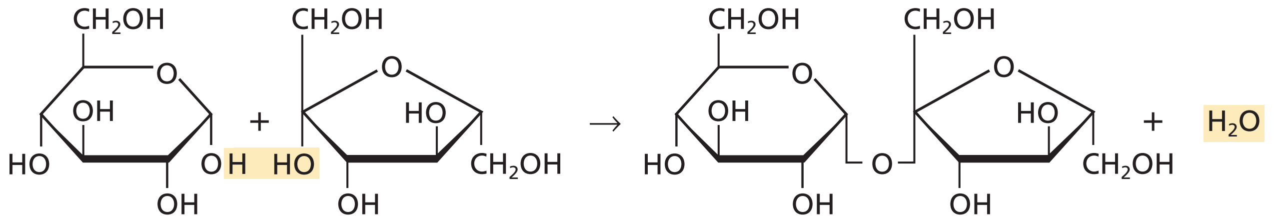
Glucose is a six-carbon sugar that has an aldehyde structure. Glucose is present in high concentration in blood because it serves as the major source of immediate energy in the body. For this reason, glucose is often called blood sugar. Closely related to glucose is galactose, which differs only in how a hydrogen and a hydroxyl group are oriented in space around one of the six carbon atoms. As you recall from Chapter 22, this relationship makes glucose and galactose stereoisomers; that is, their atoms are arranged differently in space. Fructose, also known as fruit sugar because it is the major carbohydrate in most fruits, is a six-carbon monosaccharide that has a ketone structure. Fructose is a structural isomer of glucose.

When monosaccharides are in aqueous solution, they exist in both open-chain and cyclic structures. The cyclic structures are more stable and are the predominant form of monosaccharides at equilibrium. Note in **Figure 24-8** that the carbonyl groups are present only in the open-chain structures. In the cyclic structures, they are converted to hydroxyl groups.

Figure 24-8

Glucose, galactose, and fructose are monosaccharides. In aqueous solutions, they exist in an equilibrium between their open-chain and cyclic forms, which are interconverted rapidly.





Glucose Fructose Sucrose Water

Figure 24-9

When glucose and fructose bond together, the disaccharide sucrose is formed. Note that water also is a product of this condensation reaction. Remember that each ring structure is made of carbon atoms, which are not shown for simplicity.

Disaccharides Like amino acids, monosaccharides can be linked together by a condensation reaction in which water is released. When two monosaccharides bond together, a **disaccharide** is formed. See **Figure 24-9**. The new bond formed is an ether functional group (C — O — C). Where does the water that is produced in this reaction come from?

One common disaccharide is sucrose, which is also known as table sugar because sucrose is used mainly as a sweetener. Sucrose is formed by linking glucose and fructose. Another common disaccharide is lactose, the most important carbohydrate in milk. It often is called milk sugar. Lactose is formed when glucose and galactose bond together. Some foods that contain common disaccharides are shown in **Figure 24-10a**.

Disaccharides are too large to be absorbed into the bloodstream from the human digestive system, so they must first be broken down into monosaccharides. This is accomplished by a number of enzymes in the digestive system, one of which is sucrase in the small intestine. Sucrase breaks down sucrose into glucose and fructose. Another enzyme, called lactase, breaks down lactose into glucose and galactose. Some people do not have an active form of the enzyme lactase. Unless they ingest lactase enzyme along with foods that contain milk, they experience gas, bloating, and much discomfort as lactose accumulates in their digestive systems. These people are said to be lactose intolerant.

Polysaccharides You may have seen large carbohydrate polymers referred to as complex carbohydrates in nutritional references. Another name for a complex carbohydrate is **polysaccharide**, which is a polymer of simple sugars that contains 12 or more monomer units. The same type of bond that joins two monosaccharides in a disaccharide links them together in a polysaccharide. Pasta is a good source of polysaccharides. The pasta shown in **Figure 24-10b** contains large amounts of starch, a polysaccharide from plants.

Figure 24-10

a When you have a snack of milk and cookies, you are ingesting the disaccharides lactose and sucrose.
b Pasta is rich in the polysaccharide starch.

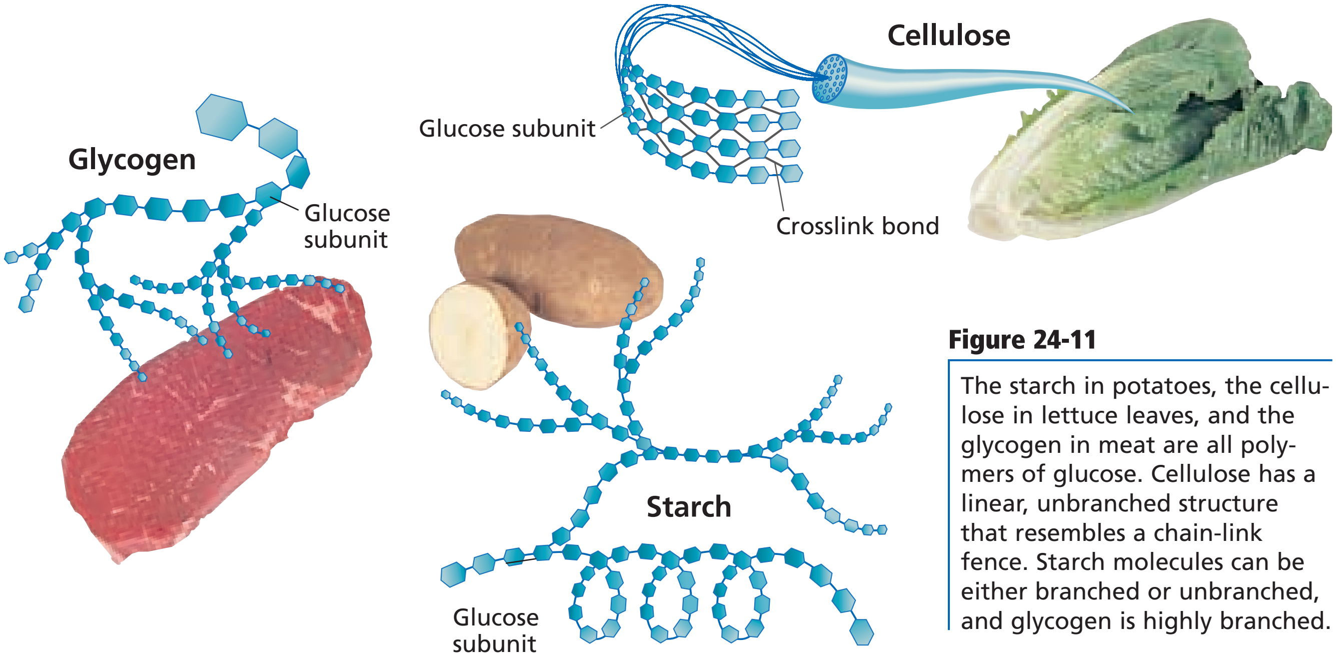


Figure 24-11

The starch in potatoes, the cellulose in lettuce leaves, and the glycogen in meat are all polymers of glucose. Cellulose has a linear, unbranched structure that resembles a chain-link fence. Starch molecules can be either branched or unbranched, and glycogen is highly branched.

Three important polysaccharides are starch, cellulose, and glycogen. All are composed solely of glucose monomers, as **Figure 24-11** illustrates. However, that's their only similarity, as all three have different properties and functions. Plants make both starch and cellulose. Starch is a soft, water-soluble molecule used to store energy, whereas cellulose is a water-insoluble polymer that forms rigid plant cell walls such as those found in wood. Glycogen is the animal counterpart of starch. It is made by animals to store energy, mostly in the liver and muscles.

How can these three polymers all be made solely of glucose monomers yet have such different properties? The answer lies in the way the bonds that link the monomers together are oriented in space. Because of this difference in bond shape, humans can digest starch but not cellulose. Digestive enzymes can't fit cellulose into their active sites due to the specific lock-and-key fit needed for enzyme action. As a result, the cellulose in the fruits, vegetables, and grains that we eat is labeled "dietary fiber" because it passes through the digestive system largely unchanged.

Section 24.2 Assessment

6. Compare the structures of monosaccharides, disaccharides, and polysaccharides. Which has the largest molecular mass? The smallest?

7. What is the main function of carbohydrates in living organisms?

8. Compare and contrast the structures of starch and cellulose. How do the structural differences affect our ability to digest these two polysaccharides?

9. **Thinking Critically** If a carbohydrate has 2^n possible isomers, where n is equal to the number of carbon atoms in the carbohydrate structure that are chiral (meaning a carbon atom with four different groups bonded to it), calculate the number of possible isomers for each of the following monosaccharides. Use **Figure 24-8** to help you.

- **a.** galactose
- **b.** glucose
- **c.** fructose

10. **Interpreting Scientific Illustrations** Draw the structure of the disaccharide sucrose, circling the ether functional group that bonds the monomer sugars together.

CONTENTS

Lipids

Objectives

- **Describe** the structures of fatty acids, triglycerides, phospholipids, and steroids.
- **Explain** the functions of lipids in living organisms.
- **Identify** some reactions that fatty acids undergo.
- **Relate** the structure and function of cell membranes.

Vocabulary

lipid
fatty acid
triglyceride
saponification
phospholipid
wax
steroid

The wax that you use to polish your car, the fat that drips out of your burger, and the vitamin D that fortifies the milk you drank for lunch—what do these diverse compounds have in common? They are all lipids.

What is a lipid?

A **lipid** is a large, nonpolar, biological molecule. Because lipids are nonpolar, they are insoluble in water. Lipids have two major functions in living organisms. They store energy efficiently, and they make up most of the structure of cell membranes. Unlike proteins and carbohydrates, lipids are not polymers with repeated monomer subunits.

Fatty acids Although lipids are not polymers, many lipids have a major building block in common. This building block is the **fatty acid**, a long-chain carboxylic acid. Most naturally occurring fatty acids contain between 12 and 24 carbon atoms. Their structure can be represented by the formula

$$CH_3(CH_2)_nCOOH$$

Most fatty acids have an even number of carbon atoms, which is a result of their being constructed two carbons at a time in enzymatic reactions.

Fatty acids can be grouped into two main categories depending on the presence or absence of double bonds between carbon atoms. Fatty acids that contain no double bonds are referred to as saturated. Those that have one or more double bonds are called unsaturated. **Figure 24-12** shows the structures of two common fatty acids. Stearic acid is an 18-carbon saturated fatty acid; oleic acid is an 18-carbon unsaturated fatty acid. What makes oleic acid unsaturated?

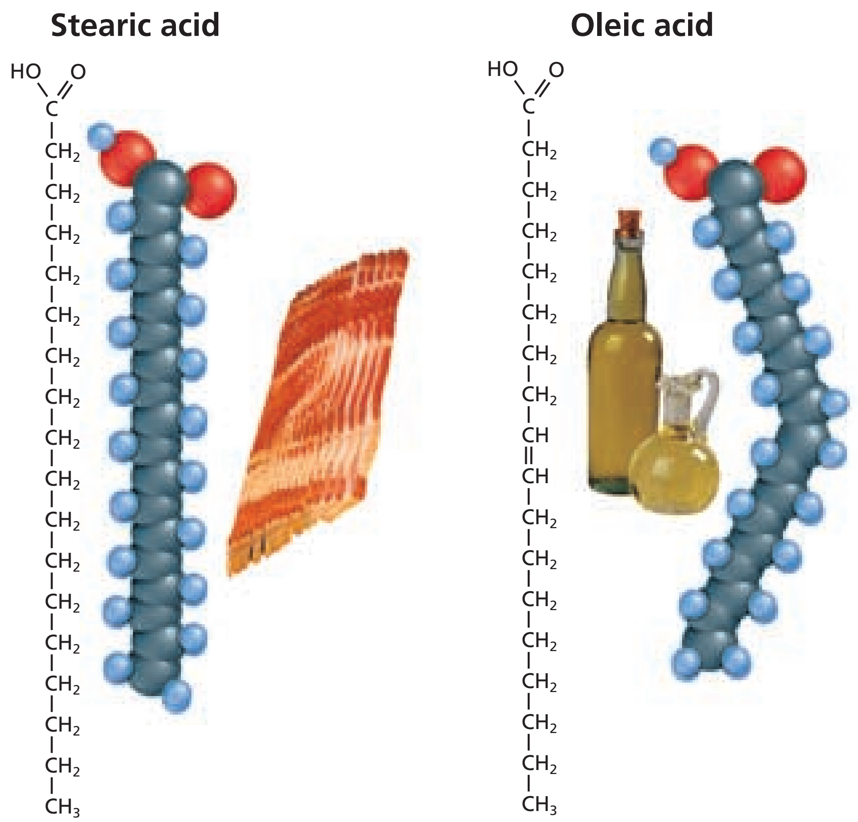
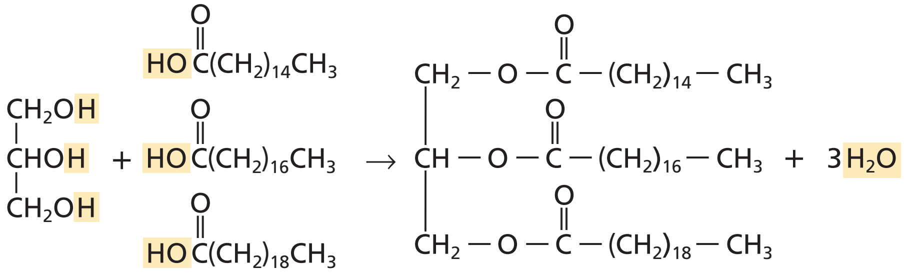


Figure 24-12

Two fatty acids abundant in our diets are the 18-carbon saturated stearic acid and the 18-carbon unsaturated oleic acid. How is the structure of the molecule affected by the presence of a double bond? Refer to **Table C-1** in Appendix C for a key to atom color conventions.



Glycerol   3 Fatty acids   A triglyceride   Water

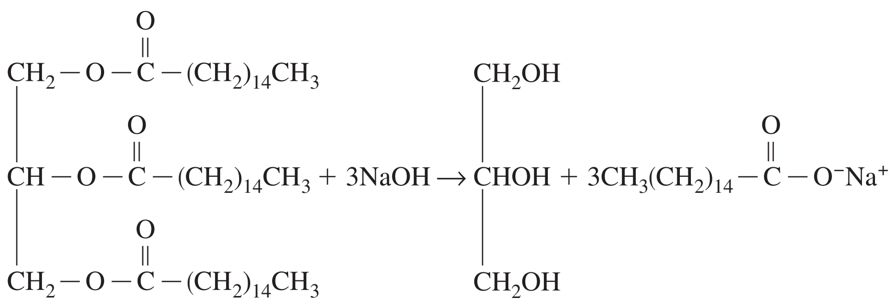
An unsaturated fatty acid can become saturated if it reacts with hydrogen. As you learned in Chapter 23, hydrogenation is an addition reaction in which hydrogen gas reacts with carbon atoms that are linked by multiple bonds. Each unsaturated carbon atom can pick up one hydrogen atom to become saturated. For example, oleic acid can be hydrogenated to form stearic acid.

The double bonds in naturally occurring fatty acids are almost all in the *cis* geometric isomer form. Recall from Chapter 22 that the *cis* isomer has identical groups oriented on the same side of the molecule around a double bond. Because of the *cis* orientation, unsaturated fatty acids have a kink, or bend, in their structure that prevents them from packing together. They don't form as many intermolecular attractions as saturated fatty acid molecules. As a result, unsaturated fatty acids have lower melting points.

Triglycerides Although fatty acids are abundant in living organisms, they are rarely found alone. They most often are found bonded to glycerol, a molecule with three carbons each containing a hydroxyl group. When three fatty acids are bonded to a glycerol backbone through ester bonds, a **triglyceride** is formed. The formation of a triglyceride is shown in **Figure 24-13**.

Triglycerides can be either solids or liquids at room temperature. If liquid, they are usually called oils. If solid at room temperature, they're called fats. Most mixtures of triglycerides from plant sources, such as corn, olive, and peanut oils, are liquids because the triglycerides contain unsaturated fatty acids that have fairly low melting points. Animal fats, such as butter, contain a larger proportion of saturated fatty acids. They have higher melting points and usually are solids at room temperature.

Fatty acids are stored in fat cells of your body as triglycerides. When energy is abundant, fat cells store the excess energy in the fatty acids of triglycerides. When energy is scarce, the cells break down the triglycerides, forming free fatty acids and glycerol. Further breakdown of the fatty acids releases the energy used to form them. Although enzymes break down triglycerides in living cells, the reaction can be duplicated outside of cells by using a strong base such as sodium hydroxide. This reaction—the hydrolysis of a triglyceride using an aqueous solution of a strong base to form carboxylate salts and glycerol—is **saponification**, shown below.



Triglyceride   A base   Glycerol   A soap

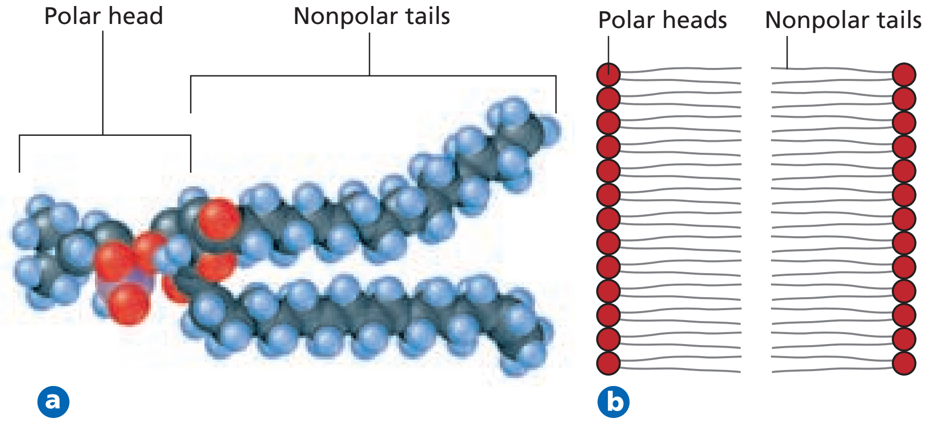
Figure 24-13

Ester bonds in a triglyceride are formed when the hydroxyl groups of glycerol combine with the carboxyl groups of the fatty acids.

Biology CONNECTION

The venom of poisonous snakes contains a class of enzymes known as phospholipases. These enzymes catalyze the breakdown of phospholipids, triglycerides in which one fatty acid has been replaced by a phosphate group. The venom of the eastern diamondback rattlesnake contains a phospholipase that hydrolyzes the ester bond at the middle carbon of phospholipids. If the larger of the two breakdown products of this reaction gets into the bloodstream, it dissolves the membranes of red blood cells, causing them to rupture. A bite from the eastern diamondback can lead to death if not treated immediately.

Figure 24-14
a A phospholipid has a polar head and two nonpolar tails. **b** The membranes of living cells are formed by a double layer of lipids called a bilayer. The polar heads face out of both sides of the bilayer, where they are in contact with the watery environment inside and outside the cell. The nonpolar tails point into the center of the bilayer.



Saponification is used to make soaps, which usually are the sodium salts of fatty acids. A soap has both a polar end and a nonpolar end. Soaps can be used to clean nonpolar dirt and oil with water because the nonpolar dirt and oil bond to the nonpolar end of the soap molecules, and the polar end of the soap molecules is soluble in water. Thus, the dirt-laden soap molecules can be rinsed away with the water. You can make soap by doing the **miniLAB** on this page.

Phospholipids Another important type of triglyceride, phospholipids, are found in greatest abundance in cellular membranes. A **phospholipid** is a triglyceride in which one of the fatty acids is replaced by a polar phosphate group. As you can see in **Figure 24-14a**, the polar part of the molecule forms

miniLAB

A Saponification Reaction

Applying Concepts The reaction between a triglyceride and a strong base such as sodium hydroxide is called saponification. In this reaction, the ester bonds in the triglyceride are hydrolyzed by the base. The sodium salts of the fatty acids, called soaps, precipitate out, and glycerol is left in solution.

Materials solid vegetable shortening, 250-mL beaker, 600-mL beaker, 6.0*M* NaOH, ethanol, saturated NaCl solution, stirring rod, hot plate, tongs, 25-mL graduated cylinder, evaporating dish, cheesecloth (20 cm × 20 cm), funnel

Procedure

1. Place a 250-mL beaker on the hot plate. Add 25 g solid vegetable shortening to the beaker. Turn the hot plate on at a medium setting.
2. As the vegetable shortening melts, slowly add 12 mL ethanol and then 5 mL 6.0*M* NaOH to the beaker. **CAUTION:** *Ethanol is flammable. NaOH causes skin burns. Wear gloves.*
3. Heat the mixture, stirring occasionally, for about 15 minutes, but do not allow it to boil.
4. When the mixture begins to thicken, use tongs to remove the beaker from the heat. Allow the beaker to cool for five minutes, then place it in a cold water bath in the 600-mL beaker.
5. Add 25 mL saturated NaCl solution to the mixture in the beaker. The soap is not very soluble and will appear as small clumps.
6. Collect the solid soap clumps by filtering them through a cheesecloth-lined funnel.
7. Using gloved hands, press the soap into an evaporating dish. Allow the soap to air dry for one or two days.
8. Remove your gloves and wash your hands.

Analysis

1. What type of bonds present in the triglycerides are broken during the saponification reaction?
2. What is the common name for the sodium salt of a fatty acid?
3. How does soap remove dirt from a surface?
4. Write a word equation for the saponification reaction in this lab.

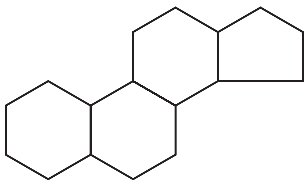
a "head," and the nonpolar fatty acids look like tails. How are the polar and nonpolar parts of a phospholipid arranged in the membranes of cells? A typical cell membrane has two layers of phospholipids, which are arranged with their nonpolar tails pointing inward and their polar heads pointing outward. See **Figure 24-14b.** This arrangement is called a lipid bilayer. Because the lipid bilayer structure acts as a barrier, the cell is able to regulate the materials that enter and leave through the membrane.

Waxes Another type of lipid, waxes, also contain fatty acids. A **wax** is a lipid that is formed by combining a fatty acid with a long-chain alcohol. The general structure of these soft, solid fats with low melting points is shown below, with *x* and *y* representing variable numbers of CH_2 groups.

$$CH_3(CH_2)_x-\overset{\overset{\large O}{\|}}{C}-O-(CH_2)_yCH_3$$

Both plants and animals make waxes. Plant leaves are often coated with wax, which prevents water loss. Notice in **Figure 24-15** how raindrops "bead up" on the leaves of a plant, indicating the presence of the waxy layer. The honeycomb of bees also is made of a wax, commonly called beeswax. Combining the 16-carbon fatty acid palmitic acid and a 30-carbon alcohol chain makes a common form of beeswax. Candles are sometimes made of beeswax because it burns slowly and evenly.

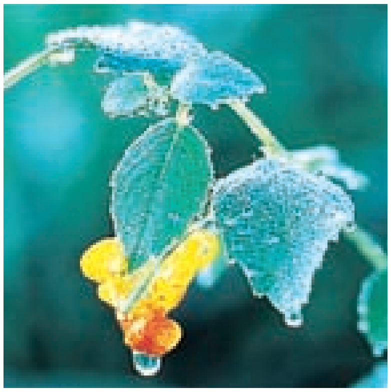
Steroids Not all lipids contain fatty acid chains. **Steroids** are lipids that have multiple cyclic rings in their structures. All steroids are built from the basic four-ring steroid structure shown below.



Some hormones, such as many sex hormones, are steroids that function to regulate metabolic processes. Cholesterol, another steroid, is an important structural component of cell membranes. Vitamin D also contains the four-ring steroid structure and plays a role in the formation of bones.

Figure 24-15

Plants produce wax that coats their leaves (top). The wax protects the leaves from drying out. The honeycomb of a beehive is constructed from beeswax (bottom).



Section 24.3 Assessment

11. Write the equation for the complete hydrogenation of the polyunsaturated fatty acid linoleic acid, $CH_3(CH_2)_4CH=CHCH_2CH=CH(CH_2)_7COOH$.

12. List an important function of each of these types of lipids.

a. triglycerides
b. phospholipids
c. waxes
d. steroids

13. Compare and contrast the structures of a steroid, a phospholipid, a wax, and a triglyceride.

14. Thinking Critically What possible solvent can be used to extract lipids from cell membranes?

15. Interpreting Scientific Illustrations Draw the general structure of a phospholipid. Label the polar and nonpolar portions of the structure.

Section 24.4 Nucleic Acids

Objectives

- **Identify** the structural components of nucleic acids.
- **Relate** the function of DNA to its structure.
- **Describe** the structure and function of RNA.

Vocabulary

nucleic acid
nucleotide

Nucleic acids are the fourth class of biological molecules that you will study. They are the information-storage molecules of the cell. This group of nitrogen-containing molecules got its name from the cellular location in which the molecules are primarily found—the nucleus. It is from this control center of cells that nucleic acids carry out their major functions.

Structure of Nucleic Acids

A **nucleic acid** is a nitrogen-containing biological polymer that is involved in the storage and transmission of genetic information. The monomer that makes up a nucleic acid is called a **nucleotide**. Each nucleotide has three parts: an inorganic phosphate group, a five-carbon monosaccharide sugar, and a nitrogen-containing structure called a nitrogen base. Examine each part of **Figure 24-16a**. Although the phosphate group is the same in all nucleotides, the sugar and the nitrogen base vary.

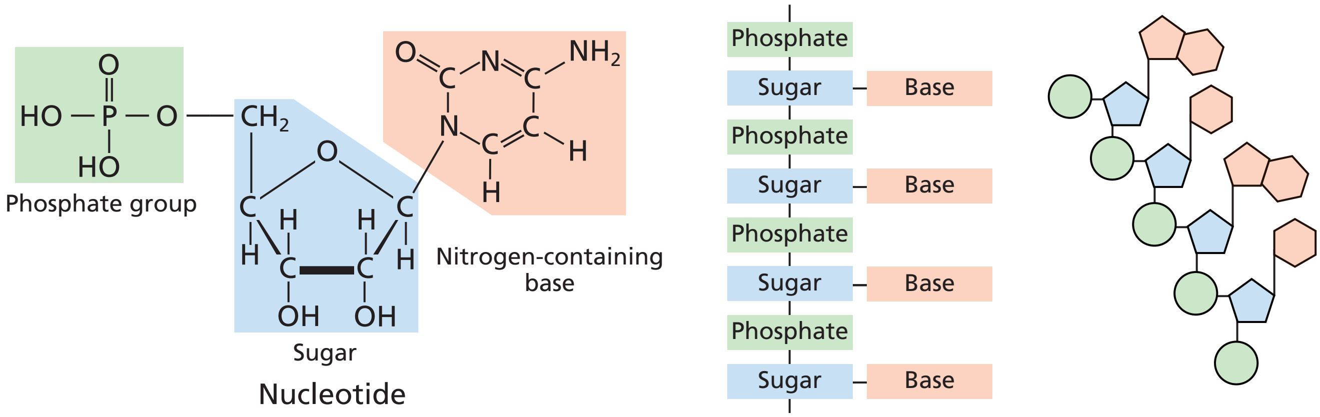
In a nucleic acid, the sugar of one nucleotide is bonded to the phosphate of another nucleotide, as shown in **Figure 24-16b**. Thus, the nucleotides are strung together in a chain, or strand, containing alternating sugar and phosphate groups. Each sugar is also bonded to a nitrogen base that sticks out from the chain. The nitrogen bases on adjoining nucleotide units are stacked one above the other in a slightly askew position, much like the steps in a staircase. You can see this orientation in **Figure 24-16c**. Intermolecular forces hold each nitrogen base close to the nitrogen bases above and below it.

DNA: The Double Helix

You've probably heard of DNA (deoxyribonucleic acid), one of the two kinds of nucleic acids found in living cells. DNA contains the master plans for building all the proteins in an organism's body.

Figure 24-16

Nucleotides are the monomers from which nucleic acid polymers are formed.



a Each nucleotide contains a nitrogen-containing base, a five-carbon sugar, and a phosphate group.

b Nucleic acids are linear chains of alternating sugars and phosphates. Attached to every sugar is a nitrogen base, which is oriented roughly perpendicular to the linear chain.

c Nucleotides are offset and thus resemble a staircase.

The structure of DNA The structure of DNA consists of two long chains of nucleotides wound together to form a spiral structure. Each nucleotide in DNA contains a phosphate group, the five-carbon sugar deoxyribose, and a nitrogen base. The alternating sugar and phosphate groups in each chain make up the outside, or backbone, of the spiral structure. The nitrogen bases are on the inside. Because the spiral structure is composed of two chains, it is known as a double helix. You can see from **Figure 24-17** that the DNA molecule is similar to a zipper in which the two ends have been twisted in opposite directions. The two sugar-phosphate backbones form the outsides of the zipper. What forms the zipper's teeth?

DNA contains four different nitrogen bases: adenine (A), thymine (T), cytosine (C), and guanine (G). As **Figure 24-18** shows, both adenine and guanine contain a double ring. Thymine and cytosine are single-ring structures. Looking back at **Figure 24-17**, you can see that each nitrogen base on one strand of the helix is oriented next to a nitrogen base on the opposite strand, in the same way that the teeth of a zipper are oriented. The side-by-side base pairs are close enough so that hydrogen bonds form between them. Because each nitrogen base has a unique arrangement of organic functional groups that can form hydrogen bonds, the nitrogen bases always pair in a specific way so that the optimum number of hydrogen bonds form. As **Figure 24-18** shows, guanine always binds to cytosine, and adenine always binds to thymine. The G—C and A—T pairs are called complementary base pairs.

It is because of complementary base pairing that the amount of adenine in a molecule of DNA always equals the amount of thymine, and the amount of cytosine always equals the amount of guanine. In 1953, James Watson and Francis Crick used this observation to make one of the greatest scientific discoveries of the twentieth century when they determined the double-helix structure of DNA. They accomplished this feat without actually carrying out many laboratory experiments themselves. Instead, they analyzed and synthesized the work of numerous scientists who had carefully carried out studies on DNA. The X-ray diffraction patterns of DNA fibers taken by Maurice Wilkins and Rosalind Franklin were of special importance because they clearly showed the dimensions of the DNA molecule and the molecule's helical structure. Watson and Crick used these results and molecular modeling techniques to build their DNA structure with balls and sticks. This discovery illustrates the importance of being able to visualize molecules in order to uncover patterns in bonding arrangements. How might such molecular modeling be done today?

The function of DNA Watson and Crick used their model to predict how DNA's chemical structure enables it to carry out its function. DNA stores the genetic information of a cell in the cell's nucleus. Before the cell divides, the DNA is copied so that the new generation of cells gets the same

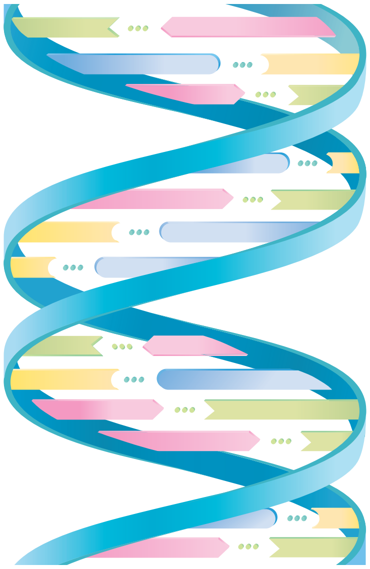


Figure 24-17

The structure of DNA is a double helix that resembles a twisted zipper.

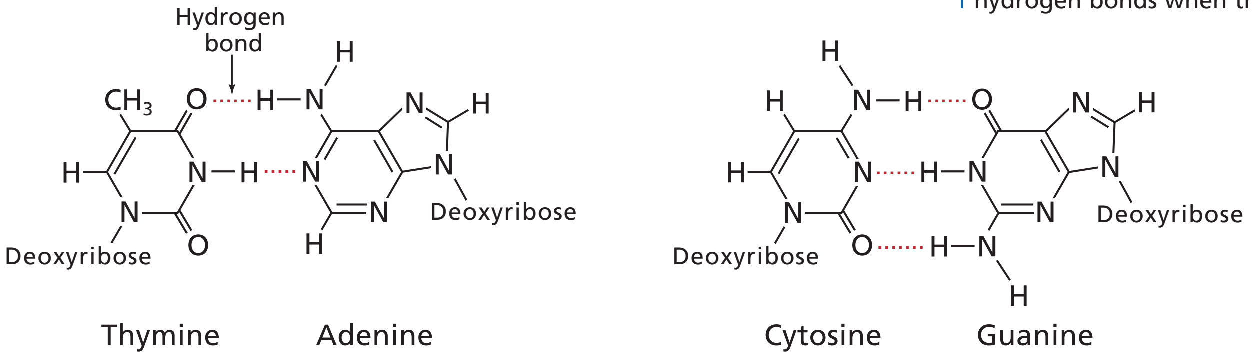


Figure 24-18

In DNA, base pairing exists between a double-ringed base and a single-ringed base. Adenine and thymine always pair, forming two hydrogen bonds between them. Guanine and cytosine always form three hydrogen bonds when they pair.

genetic information. Having determined that the two chains of the DNA helix are complementary, Watson and Crick realized that complementary base pairing provides a mechanism by which the genetic material of a cell is copied. The **problem-solving LAB** shows how DNA copies, or replicates, itself.

The four nitrogen bases of DNA serve as the letters of the alphabet in the information-storage language of living cells. The specific sequence of these letters represents an organism's master instructions, just as the sequence of letters in the words of this sentence convey special meaning. The sequence of bases is different in every species of organism, allowing for an enormous diversity of life forms—all from a language that uses only four letters. It is estimated that the DNA in a human cell has about three billion complementary base pairs, arranged in a sequence unique to humans.

problem-solving LAB

How does DNA replicate?

Formulating Models DNA must be copied, or replicated, before a cell can divide so that each of the two new cells that are formed by cell division has a complete set of genetic instructions. It is very important that the replicating process be accurate; the new DNA molecules must be identical to the original. Watson and Crick noticed that their model for the three-dimensional structure of DNA provided a mechanism for accurate replication.

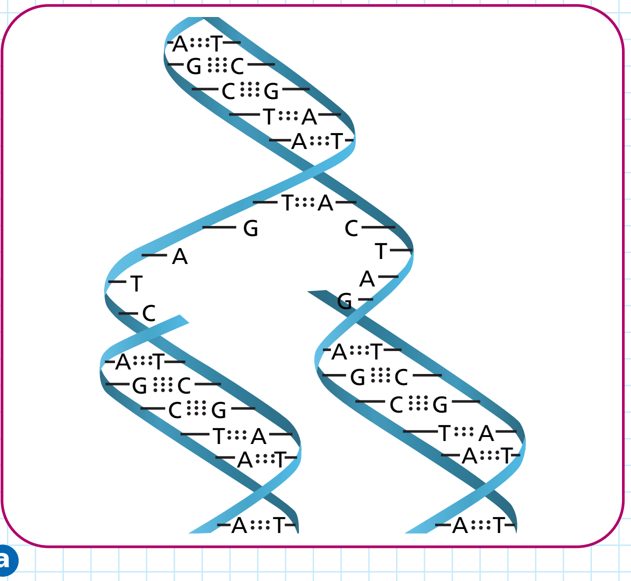
When DNA begins to replicate, the two nucleotide strands start to unzip. An enzyme breaks the hydrogen bonds between the nitrogen bases, and the strands separate to expose the nitrogen bases. Other enzymes deliver free nucleotides from the surrounding medium to the exposed nitrogen bases, adenine hydrogen-bonding with thymine and cytosine bonding with guanine. Thus, each strand builds a complementary strand by base pairing with free nucleotides. This process is shown in **Diagram a**. When the free nucleotides have been hydrogen-bonded into place, their sugars and phosphates bond covalently to those on adjacent nucleotides to form the new backbone. Each strand of the original DNA molecule is now bonded to a new strand.

Analysis

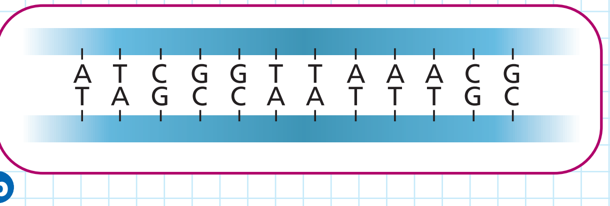
Diagram b shows a small segment of a DNA molecule. Copy the base sequence onto a clean sheet of paper, being careful not to make copying errors. Show the steps of replication to produce two segments of the DNA.

Thinking Critically

1. How does the base sequence of a newly synthesized strand compare with the original strand to which it is bonded?
2. If the original DNA segment is colored red and the free nucleotides are colored blue, what pattern of colors will the newly replicated DNA segments have? Will all new segments have the same color pattern? What does this pattern mean?
3. What would happen if you had made an error when copying the base sequence onto your sheet of paper? How might an organism be affected if this error had occurred during replication of its DNA?



a



b

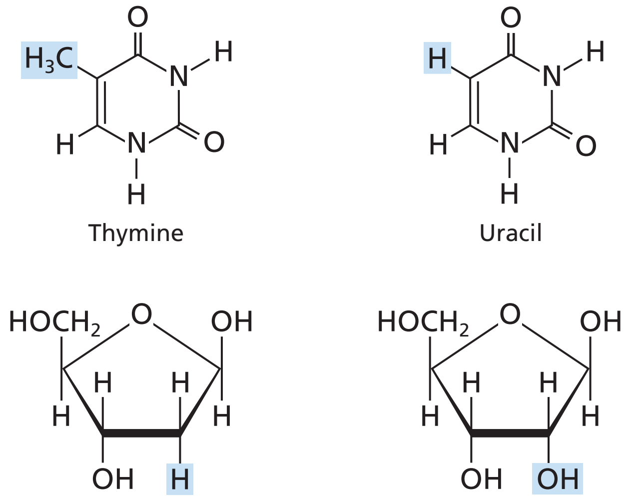


Figure 24-19

DNA and RNA are nucleic acids with some important differences in structure. DNA contains thymine; RNA contains uracil, which lacks a methyl group. DNA's sugar, deoxyribose, has a hydrogen in one position instead of the hydroxyl group that ribose has.

RNA

RNA (ribonucleic acid) also is a nucleic acid. Its general structure differs from that of DNA in three important ways. As you know, DNA contains the nitrogen bases adenine, cytosine, guanine, and thymine. RNA contains adenine, cytosine, guanine, and uracil; thymine is never found in RNA. Secondly, RNA contains the sugar ribose. DNA contains the sugar deoxyribose, which has a hydrogen atom in place of a hydroxyl group at one position. Compare these different structures shown in **Figure 24-19**.

The third difference between DNA and RNA arises as a result of these structural differences. DNA is normally arranged in a double helix in which hydrogen bonding links the two chains together through their bases. RNA is usually single stranded, with no such hydrogen bonds forming.

Whereas DNA functions to store genetic information, RNA allows cells to use the information found in DNA. You have learned that the genetic information of a cell is contained in the sequence of nitrogen bases in the DNA molecule. Cells use this base sequence to make RNA with a corresponding sequence. The RNA is then used to make proteins, each with an amino acid sequence that is determined by the order of nitrogen bases in RNA. The translation of the base-sequence language of nucleic acids into the amino acid-sequence language of proteins is known as the genetic code. Because proteins are the molecular tools that actually carry out most activities in a cell, the DNA double helix is ultimately responsible for controlling the thousands of chemical reactions that take place.

Section 24.4 Assessment

16. List the three chemical structures that make up a nucleotide.

17. Compare and contrast the structures and functions of DNA and RNA.

18. A sample of nucleic acid was determined to contain adenine, uracil, cytosine, and guanine. What type of nucleic acid is this?

19. **Thinking Critically** Analyze the structure of nucleic acids to determine what structural feature makes them acidic.

20. **Predicting** What is the genetic code? Predict what might happen to a protein if the DNA that coded for the protein contained the wrong base sequence.

Section 24.5

Metabolism

Objectives

- **Distinguish** between anabolism and catabolism.
- **Describe** the role of ATP in metabolism.
- **Compare** and **contrast** the processes of photosynthesis, cellular respiration, and fermentation.

Vocabulary

metabolism
catabolism
anabolism
ATP
photosynthesis
cellular respiration
fermentation

You've now studied the four major kinds of biological molecules and learned that they all are present in the food you eat. What happens to these molecules after they enter your body?

Anabolism and Catabolism

Many thousands of chemical reactions take place in the cells of a living organism. The set of reactions carried out by an organism is its **metabolism**. Why are so many reactions involved in metabolism? Living organisms must accomplish two major functions in order to survive. They have to extract energy from nutrients in forms that they can use immediately as well as store for future use. In addition, they have to use nutrients to make building blocks for synthesizing all of the molecules needed to carry out their life functions. These processes are summarized in **Figure 24-20**.

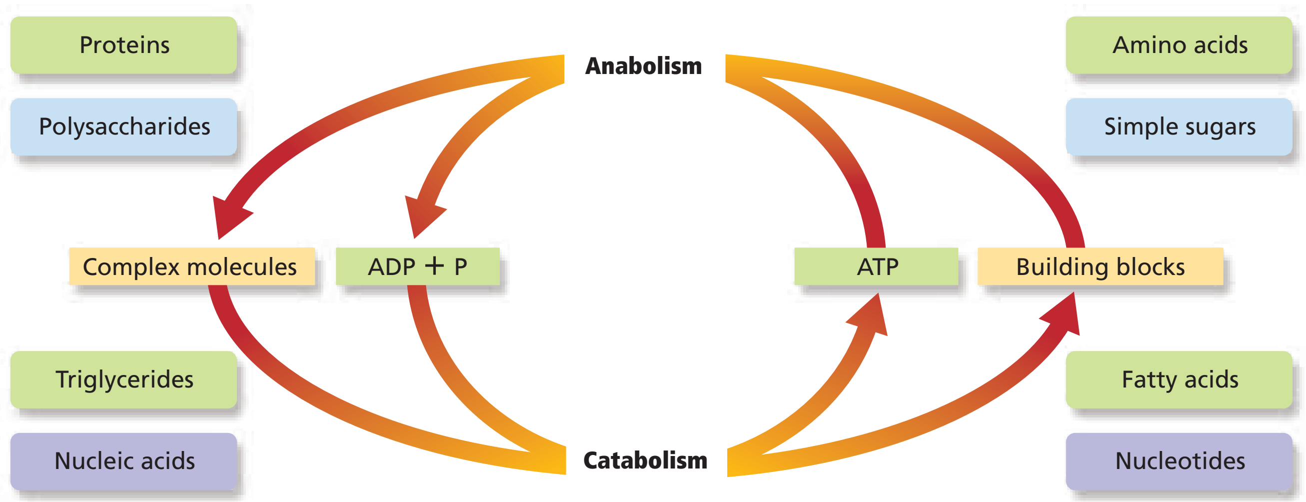
The term **catabolism** refers to the metabolic reactions that break down complex biological molecules such as proteins, polysaccharides, triglycerides, and nucleic acids for the purposes of forming smaller building blocks and extracting energy. After you eat a meal of spaghetti and meatballs, your body immediately begins to break down the starch polymer in the spaghetti into glucose. The glucose is then broken down into smaller molecules in a series of energy-releasing catabolic reactions. Meanwhile, the protein polymers in the meatballs are catabolized into amino acids.

The term **anabolism** refers to the metabolic reactions that use energy and small building blocks to synthesize the complex molecules needed by an organism. After your body has extracted the energy from the starch in pasta, it uses that energy and the amino-acid building blocks produced from the meat proteins to synthesize the specific proteins that allow your muscles to contract, catalyze metabolic reactions, and carry out many other functions in your body.

Figure 24-20 shows the relationship between catabolism and anabolism. The simple building-block molecules that are listed on the right side of the diagram are used to build the complex molecules that are listed on the left side of the diagram. As the arrow moves from right to left, anabolic reactions

Figure 24-20

A large number of different metabolic reactions take place in living cells. Some involve breaking down nutrients to extract energy; these are catabolic processes. Others involve using energy to build large biological molecules; these reactions are anabolic processes.



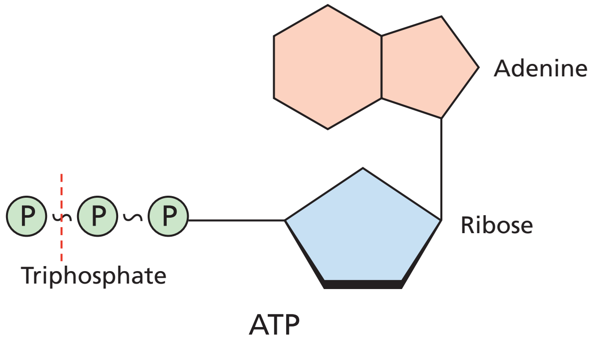


Figure 24-21

ATP is a nucleotide that contains an adenine nitrogen base, a ribose sugar, and three phosphate groups. When the final phosphate group is removed from ATP, as modeled by the red dotted line, ADP is formed and energy is released.

take place. As the lower arrow moves from left to right, catabolic processes take place and the complex molecules are broken down into their smaller building blocks.

ATP Catabolism and anabolism are linked by common building blocks that catabolic reactions produce and anabolic reactions use. A common form of potential chemical energy also links the two processes. **ATP** (adenosine triphosphate) is a nucleotide that functions as the universal energy-storage molecule in living cells. During catabolic reactions, cells harness the chemical energy of foods and store it in the bonds of ATP. When these bonds are broken, the chemical energy is released and used by cells to drive anabolic reactions that might not otherwise occur. Most cellular reactions have an efficiency of only about 40 percent at best; the remaining 60 percent of the energy in food is lost as heat, which is used to keep your body warm.

The structure of ATP is shown in **Figure 24-21**. During catabolic reactions, cells produce ATP by adding an inorganic phosphate group to the nucleotide adenosine diphosphate (ADP) in an endothermic reaction. One mole of ATP stores approximately 30.5 kJ of energy under normal cellular conditions. During anabolism, the reverse reaction occurs. ATP is broken down to form ADP and inorganic phosphate in an exothermic reaction. Approximately 30.5 kJ of energy is released from each mole of ATP.

Photosynthesis

What is the source of the energy that fuels metabolism? For most living things, certain wavelengths of sunlight provide all of this energy. Some bacteria and the cells of all plants and algae, including the brown algae shown in **Figure 24-22**, are able to capture light energy and convert some of it to chemical energy. Animals can't capture light energy, so they get energy by eating plants or by eating other animals that eat plants. The process that converts energy from sunlight to chemical energy in the bonds of carbohydrates is called **photosynthesis**. During the complex process of photosynthesis, carbon dioxide and water provide the carbon, hydrogen, and oxygen atoms that make up carbohydrates and oxygen gas, which also is formed. The following net reaction takes place during photosynthesis.

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} + \text{light energy} \rightarrow \underset{\text{Glucose}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

Photosynthesis results in the reduction of the carbon atoms in carbon dioxide as glucose is formed. During this redox process, oxygen atoms in water are oxidized to oxygen gas.

Figure 24-22

These giant seaweeds, called kelps, must grow close to the ocean's surface where light is available for photosynthesis. They cannot grow in the dark depths where sunlight does not penetrate the seawater.

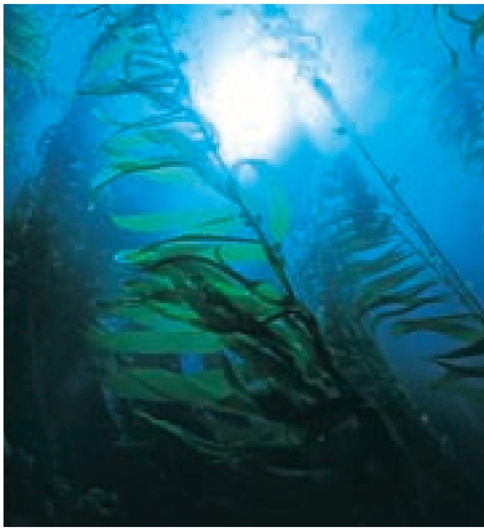


Figure 24-23

These runners will need large amounts of energy if they are to complete the race. This energy is stored in the bonds of ATP in their cells.

Cellular Respiration

Most organisms need oxygen to live. Oxygen that is produced during photosynthesis is used by living things during **cellular respiration**, the process in which glucose is broken down to form carbon dioxide, water, and large amounts of energy. Cellular respiration is the major energy-producing process in living organisms. **Figure 24-23** shows one use of energy in the body. This energy is stored in the bonds of ATP, and a maximum of 38 moles of ATP are produced for every mole of glucose that is catabolized. Cellular respiration is a redox process; the carbon atoms in glucose are oxidized while oxygen atoms in oxygen gas are reduced to the oxygen in water. The net reaction that takes place during cellular respiration is

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{energy}$$

Glucose Oxygen Carbon dioxide Water

Note that the net equation for cellular respiration is the reverse of the net equation for photosynthesis. You will learn in Chapter 26 how these two processes complement each other in nature.

Careers Using Chemistry

Personal Trainer

Are you interested in health and fitness? Are you good at motivating people to do their best? Then consider a career as a personal trainer.

Personal trainers help people set up and follow exercise programs. The trainers design the programs to get specific results, such as weight loss, muscle building, improved endurance, or preparation for a sport. They can create programs for people who are older or injured. Trainers work in gyms, health clubs, and corporate fitness centers. The frequency with which trainers see a client varies according to the client's needs.

Fermentation

During cellular respiration, glucose is completely oxidized, and oxygen gas is required to act as the oxidizing agent. Can cells extract energy from glucose in the absence of oxygen? Yes, but not nearly as efficiently. Without oxygen, only a fraction of the chemical energy of glucose can be released. Whereas cellular respiration produces 38 moles of ATP for every mole of glucose catabolized in the presence of oxygen, only two moles of ATP are produced per mole of glucose that is catabolized in the absence of oxygen. This provides enough energy for oxygen-deprived cells so that they don't die. The process in which glucose is broken down in the absence of oxygen is known as **fermentation**. There are two common kinds of fermentation. In one, ethanol and carbon dioxide are produced. In the other, lactic acid is produced.

Alcoholic fermentation Yeast and some bacteria can ferment glucose to produce the alcohol ethanol.

$$C_6H_{12}O_6 \longrightarrow 2CH_3CH_2OH + 2CO_2 + \text{energy}$$

Glucose Ethanol Carbon dioxide

Figure 24-24

Bread dough is heavy before yeast cells begin to ferment the carbohydrates (left). After fermentation has produced carbon dioxide, the dough becomes lighter and fluffier as it rises (right).

This reaction, called alcoholic fermentation, is important to certain segments of the food industry, as you can see in **Figure 24-24**. Alcoholic fermentation is needed to make bread dough rise, form tofu from soybeans, and produce the ethanol in alcoholic beverages. Another use of the ethanol that is produced by yeast is as an additive to gasoline, called gasohol. You can observe yeast cells fermenting sugar in the **CHEMLAB** at the end of this chapter.

Lactic acid fermentation Have you ever gotten muscle fatigue while running a race? During strenuous activity, muscle cells often use oxygen faster than it can be supplied by the blood. When the supply of oxygen is depleted, cellular respiration stops. Although animal cells can't undergo alcoholic fermentation, they can produce lactic acid and a small amount of energy from glucose through lactic acid fermentation.

$$\underset{\text{Glucose}}{C_6H_{12}O_6} \longrightarrow \underset{\text{Lactic acid}}{2CH_3CH(OH)COOH} + \text{energy}$$

The lactic acid that is produced is moved from the muscles through the blood to the liver. There, it is converted back into glucose that can be used in catabolic processes to yield more energy once oxygen becomes available. However, if lactic acid builds up in muscle cells at a faster rate than the blood can remove it, muscle fatigue results. Buildup of lactic acid is what causes a burning pain in the muscle during strenuous exercise.

Section 24.5 Assessment

21. Compare and contrast the processes of anabolism and catabolism.

22. Explain the role ATP plays in the metabolism of living organisms.

23. Decide whether each of the following processes is anabolic or catabolic.

- **a.** photosynthesis
- **b.** cellular respiration
- **c.** fermentation

24. **Thinking Critically** Why is it necessary to use sealed casks when making wine?

25. **Calculating** How many moles of ATP would a yeast cell produce if six moles of glucose were oxidized completely in the presence of oxygen? How many moles of ATP would the yeast cell produce from six moles of glucose if the cell were deprived of oxygen? For more help, refer to *Arithmetic Operations* in the **Math Handbook** on page 887 of this textbook.

Alcoholic Fermentation in Yeast

Yeast cells are able to metabolize many types of sugars. In this experiment, you will observe the fermentation of sugar by baker's yeast. When yeast cells are mixed with a sucrose solution, they must first hydrolyze the sucrose to glucose and fructose. Then the glucose is broken down in the absence of oxygen to form ethanol and carbon dioxide. You can test for the production of carbon dioxide by using a CBL pressure sensor to measure an increase in pressure.

Problem

What is the rate of alcoholic fermentation of sugar by baker's yeast?

Objectives

- **Measure** the pressure of carbon dioxide produced by the alcoholic fermentation of sugar by yeast.
- **Calculate** the rate of production of carbon dioxide by the alcoholic fermentation of sugar by yeast.

Materials

CBL system
graphing calculator
ChemBio program
Vernier pressure sensor
link cable
CBL-DIN cable
test tube with #5 rubber-stopper assembly
5% sucrose solution
ring stand
stirring rod
600-mL beaker
thermometer
basting bulb
hot and cold water
yeast suspension
vegetable oil
utility clamp
10-mL graduated cylinders (2)
pipette

Safety Precautions

- **Always wear safety goggles and an apron in the lab.**
- **Do not use the thermometer as a stirring rod.**

Pre-Lab

1. Reread the section of this chapter that describes alcoholic fermentation.
2. Write the chemical equation for the alcoholic fermentation of glucose.
3. Read the entire **CHEMLAB**.
4. Prepare all written materials that you will take into the laboratory. Be sure to include safety precautions and procedure notes.
5. Form a hypothesis about how the pressure inside the test tube is related to the production of carbon dioxide during the reaction. Refer to the ideal gas law in your explanation.
6. Why is temperature control an essential feature of the **CHEMLAB**?

Procedure

1. Load the ChemBio program into your graphing calculator. Connect the CBL and calculator with the link cable. Connect the pressure sensor to the CBL with a CBL-DIN cable.
2. Prepare a water bath using the 600-mL beaker. The beaker should be about two-thirds full of water. The water temperature should be between 36°C and 38°C.
3. Set up the test tube, ring stand, and utility clamp as shown in the figure. Obtain about 3 mL yeast suspension in a 10-mL graduated cylinder, and pour it into the test tube. Obtain about 3 mL 5% sucrose solution in a 10-mL graduated cylinder. Add the sucrose solution to the yeast in the test tube. Stir to mix. Pour enough vegetable oil on top of the mixture to completely cover the surface.

4. Place the stopper assembly into the test tube. Make sure it has an airtight fit. Leave both valves of the assembly open to the atmosphere.
5. While one lab partner does step 5, the other partner should do steps 6 and 7. Lower the test tube into the water bath and allow it to incubate for 10 minutes. Keep the temperature of the water bath between 36°C and 38°C by adding small amounts of hot or cold water with the basting bulb as needed.

6. Start the ChemBio program. Choose 1:SET UP PROBES under MAIN MENU. Choose 1 for number of probes. Choose 3:PRESSURE under SELECT PROBE. Enter 1 for Channel. Choose 1:USE STORED for CALIBRATION. Choose 1:ATM for PRESSURE UNITS.
7. Choose 2:COLLECT DATA under MAIN MENU. Choose 2:TIME GRAPH under DATA COLLECTION. Use time between sample seconds = 10. Use number of samples = 60. (This will give you 600 seconds or 10 minutes of data). Choose 1:USE TIME SETUP under CONTINUE? Set Ymin = 0.8, Ymax = 1.3, and Yscl = 0.1. Do not press ENTER until the test tube has finished incubating.
8. After the test tube has incubated for ten minutes, close the valve attached to the stopper. Make sure the valve near the pressure sensor is open to the sensor. Start measuring the gas pressure by pressing ENTER. Monitor the pressure reading on the CBL unit. If the pressure exceeds 1.3 atm, the stopper can pop off. Open the air valve on the pressure sensor to release this excess gas pressure.
9. After ten minutes, the data collection will stop. Open the air valve on the stopper. If needed, you can run a second trial by closing the air valve and choosing 2:YES to REPEAT? If you are finished, press 1:NO.

Cleanup and Disposal

1. Rinse out and wash all items.
2. Rinse the yeast suspension/sucrose/vegetable oil mixture down the sink with large amounts of water.
3. Return all lab equipment to its proper place.

Analyze and Conclude

1. **Making and Using Graphs** Choose 3:VIEW GRAPH from the MAIN MENU. Make a sketch of the graph. (You also may want to record the data table by using 4:VIEW DATA.)
2. **Interpreting Data** The rate of carbon dioxide production by the yeast can be found by calculating the slope of the graph. Return to the MAIN MENU and choose 5:FIT CURVE. Choose 1:LINEAR L1, L2. The slope will be listed under LINEAR as "A" of Y = A*X + B. Record this value.
3. **Communicating** How does your rate of carbon dioxide production compare with the rates of other members of the class?
4. **Analyzing** Why did you add vegetable oil to the test tube in step 3?
5. **Error Analysis** Suppose that the pressure does not change during a trial. What might be some possible reasons for this?

Real-World Chemistry

1. Yeast is used in baking bread because the carbon dioxide bubbles make the bread rise. The other product of alcoholic fermentation is ethanol. Why can't you taste this alcohol when you eat bread?
2. How would the appearance of a loaf of bread be different if you used twice as much yeast as the recipe called for?

Everyday Chemistry

Sense of Smell

Take a deep breath. What do you smell? Maybe it's the eraser on your pencil, some flowers outside your window, an apple pie coming out of the oven, or even stinky gym shoes on the floor. Your sense of smell, otherwise known as olfaction, tells you a lot about the world around you.

Fitting In

How exactly do you smell odors? If you said that you smell with your nose, you are only partially correct. The nose you see when you look in the mirror doesn't actually detect odors. Its job is to pull odor molecules, known as odorants, into your nasal passages when you breathe.

The air you inhale carries odorants to a small region located high inside your nasal passage just below and between your eyes. The tissues of this region contain nerve cells that have hairlike fibers called cilia on one end. When receptors located on the cilia are stimulated by odorants, the nerve cells send messages to the brain. The brain then identifies the odors you smell.

The exact manner in which receptors detect odorants is not entirely understood. However, researchers have found evidence to suggest that it involves the shapes of both the receptors and the odorants. Receptors are usually large, globular protein molecules that are similar in shape to enzymes. Their surfaces contain small crevices. An odorant must fit into and bind with a crevice on the surface of the receptor much as a substrate molecule fits into and binds with the active site on the surface of an enzyme. Each type of receptor has a uniquely shaped crevice on its surface that binds only with an odorant of a particular shape.

Not By Shape Alone

The process of smelling is not that simple, however. Scientists have discovered that shape is not the only property that determines whether an odorant will bind with a receptor. Odorant molecules must be able to travel through air and they must be able to dissolve in the fluids of the nasal passages. In addition, some research suggests that odor receptors can detect the energy levels of the odorants. An odorant with exactly the right energy will vibrate in such a way that it produces a response in the receptor. This may be what causes the nerve cell to send a signal to the brain.

So Many Odors

How many odors do you think you can recognize? If your olfactory system is at its best, you can distinguish about 10 000 different odors. Does this mean that you have more than 10 000 different types of olfactory receptors? The answer is no. In fact, you have fewer than 1000 different types of olfactory receptors.

As researchers searched for an explanation of how the olfactory receptors recognize so many different odors, they found that the olfactory system uses a combination of receptors for each odor. A single odorant can be recognized by more than one receptor because different receptors respond to different parts of the same odorant molecule. Rather than responding to a signal from a single receptor for each odor, the brain interprets a combination of signals from several receptors in order to identify a particular odor. In this way, a limited number of receptors can be used to identify a large number of odors.

Testing Your Knowledge

1. **Relating Concepts** How is the receptor-odorant relationship similar to an enzyme-substrate relationship?
2. **Applying** How might fragrance designers benefit from an understanding of how the shape of an odorant stimulates a receptor?

Summary

24.1 Proteins

- Proteins are biological polymers made of amino acids that are linked together by peptide bonds.
- Protein chains fold into intricate three-dimensional structures.
- Many proteins function as enzymes, which are highly specific and powerful biological catalysts. Other proteins function to transport important chemical substances, or provide structure in organisms.

24.2 Carbohydrates

- Monosaccharides, known as simple sugars, are aldehydes or ketones that also have multiple hydroxyl groups.
- Bonding two simple sugars together forms a disaccharide such as sucrose or lactose.
- Polysaccharides such as starch, cellulose, and glycogen are polymers of simple sugars.
- Carbohydrates function in living things to provide immediate and stored energy.

24.3 Lipids

- Fatty acids are long-chain carboxylic acids that usually have between 12 and 24 carbon atoms.
- Saturated fatty acids have no double bonds; unsaturated fatty acids have one or more double bonds.
- Fatty acids can be linked to glycerol backbones to form triglycerides.
- The membranes of living cells have a lipid bilayer structure.
- Steroids are lipids that have a multiple-ring structure.

24.4 Nucleic Acids

- Nucleic acids are polymers of nucleotides, which consist of a nitrogen base, a phosphate group, and a sugar.
- DNA contains deoxyribose sugar and the nitrogen bases adenine, cytosine, guanine, and thymine.
- RNA contains ribose sugar and the nitrogen bases adenine, cytosine, guanine, and uracil.
- DNA functions to store the genetic information in living cells and transmit it from one generation of cells to the next. RNA functions in protein synthesis.

24.5 Metabolism

- Metabolism is the sum of the many chemical reactions that go on in living cells.
- Catabolism refers to reactions that cells undergo to extract energy and chemical building blocks from large biological molecules.
- Anabolism refers to the reactions through which cells use energy and small building blocks to build the large biological molecules needed for cell structures and for carrying out cell functions.
- During photosynthesis, cells use carbon dioxide, water, and light energy to produce carbohydrates and oxygen.
- During cellular respiration, cells break down carbohydrates in the presence of oxygen gas to produce carbon dioxide and water. Energy released is stored as chemical potential energy in the molecule ATP.
- In the absence of oxygen, cells can carry out either alcoholic or lactic acid fermentation.

Vocabulary

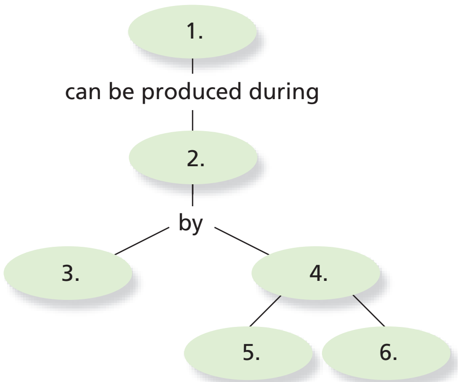
- active site (p. 778)
- amino acid (p. 776)
- anabolism (p. 792)
- ATP (p. 793)
- carbohydrate (p. 781)
- catabolism (p. 792)
- cellular respiration (p. 794)
- denaturation (p. 778)
- disaccharide (p. 782)
- enzyme (p. 778)
- fatty acid (p. 784)
- fermentation (p. 794)
- lipid (p. 784)
- metabolism (p. 792)
- monosaccharide (p. 781)
- nucleic acid (p. 788)
- nucleotide (p. 788)
- peptide (p. 777)
- peptide bond (p. 777)
- phospholipid (p. 786)
- photosynthesis (p. 793)
- polysaccharide (p. 782)
- protein (p. 775)
- saponification (p. 785)
- steroid (p. 787)
- substrate (p. 778)
- triglyceride (p. 785)
- wax (p. 787)

CHAPTER 24 ASSESSMENT

Go to the Chemistry Web site at **science.glencoe.com** *or use the* **Chemistry CD-ROM** *for additional Chapter 24 Assessment.*

Concept Mapping

26. Complete the concept map using the following terms: lactic acid, ATP, cellular respiration, metabolism, alcoholic, fermentation.



Mastering Concepts

27. What should you call a chain of eight amino acids? A chain of 200 amino acids? (24.1)

28. Name five parts of your body that are made of structural proteins. (24.1)

29. Describe two common shapes found in the three-dimensional folding of proteins. (24.1)

30. Name the organic functional groups in the side chains of the following amino acids. (24.1)

a. glutamine
b. serine
c. glutamic acid
d. lysine

31. Explain how the active site of an enzyme functions. (24.1)

32. Name the amino acids represented by each of the following abbreviations. (24.1)

a. Gly
b. Tyr
c. Trp
d. Phe
e. Glu
f. His

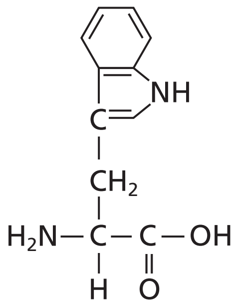
33. Name an amino acid that has an aromatic ring in its side chain. (24.1)

34. Name two nonpolar and two polar amino acids. (24.1)

35. Is the dipeptide lysine-valine the same compound as the dipeptide valine-lysine? Explain. (24.1)

36. How do enzymes lower the activation energy for a reaction? (24.1)

37. The structure shown is tryptophan. Describe some of the properties you would expect tryptophan to have, based on its structure. In what class of large molecules do you think tryptophan is a building block? (24.1)



38. Most proteins with a globular shape are oriented so that they have mostly nonpolar amino acids on the inside and polar amino acids located on the outer surface. Does this make sense in terms of the nature of the cellular environment? Explain. (24.1)

39. Classify the following carbohydrates as monosaccharides, disaccharides, or polysaccharides. (24.2)

a. starch
b. glucose
c. sucrose
d. ribose
e. cellulose
f. glycogen
g. fructose
h. lactose

40. Name two isomers of glucose. (24.2)

41. What kind of bond is formed when two monosaccharides combine to form a disaccharide? (24.2)

42. Give a scientific term for each of the following. (24.2)

a. blood sugar
b. fruit sugar
c. table sugar
d. milk sugar

43. Explain how the different bonding arrangements in cellulose and starch give them such different properties. (24.2)

44. The disaccharide maltose is formed from two glucose monomers. Draw its structure. (24.2)

45. Hydrolysis of cellulose, glycogen, and starch produces only one monosaccharide. Why is this so? What monosaccharide is produced? (24.2)

46. Digestion of disaccharides and polysaccharides cannot take place in the absence of water. Why do you think this is so? Include an equation in your answer. (24.2)

47. Draw the structure of the open-chain form of fructose. Circle all chiral carbons, and then calculate the number of stereoisomers with the same formula as fructose. (24.2)

48. Compare and contrast the structures of a triglyceride and a phospholipid. (24.3)

49. Predict whether a triglyceride from beef fat or a triglyceride from olive oil will have a higher melting point. Explain your reasoning. (24.3)

50. Explain how the structure of soaps makes them effective cleaning agents. (24.3)

51. Draw a portion of a lipid bilayer membrane, labeling the polar and nonpolar parts of the membrane. (24.3)

52. Where and in what form are fatty acids stored in the body? (24.3)

53. What type of lipid does not contain fatty acid chains? Why are these molecules classified as lipids? (24.3)

54. Draw the structure of the soap sodium palmitate (palmitate is the conjugate base of the 16-carbon saturated fatty acid, palmitic acid) and label its polar and nonpolar ends. (24.3)

55. What three structures make up a nucleotide? (24.4)

56. Name two nucleic acids found in organisms. (24.4)

57. Explain the roles of DNA and RNA in the production of proteins. (24.4)

58. Where in living cells is DNA found? (24.4)

59. Describe the types of bonds and attractions that link the monomers together in a DNA molecule. (24.4)

60. In the double helical structure of DNA, the base guanine is always bonded to cytosine and adenine is always bonded to thymine. What do you expect to be the relative proportional amounts of A, T, C, and G in a given length of DNA? (24.4)

61. One strand in a DNA molecule has the following base sequence. What is the base sequence of the other strand in the DNA molecule? (24.4)

C-C-G-T-G-G-A-C-A-T-T-A

62. Is digestion an anabolic or a catabolic process? Explain. (24.5)

63. Compare the net reactions for photosynthesis and cellular respiration with respect to reactants, products, and energy. (24.5)

Mastering Problems

Protein Structure (24.1)

64. How many peptide bonds are present in a peptide that has five amino acids?

65. How many peptides, each containing four different amino acids, can be made from Phe, Lys, Pro, and Asp? List the peptides, using the three-letter abbreviations for the amino acids.

66. The average molecular mass of an amino acid is 110 g/mol. Calculate the approximate number of amino acids in a protein that has a molecular mass of 36 500 g/mol.

Calculations with Lipids (24.3)

67. The fatty acid palmitic acid has a density of 0.853 g/mL at 62°C. What will be the mass of a 0.886-L sample of palmitic acid at that temperature?

68. How many moles of hydrogen gas are required for complete hydrogenation of one mole of linolenic acid, whose structure is shown below? Write a balanced equation for the hydrogenation reaction.

$$CH_3CH_2CH{=}CHCH_2CH{=}CHCH_2CH{=}CH(CH_2)_7COOH$$

Linolenic acid

69. A chicken egg contains about 213 mg of cholesterol. Calculate how many moles of cholesterol this represents if the molecular mass of cholesterol is 386.

70. Calculate the number of moles of sodium hydroxide needed in the saponification of 16 moles of a triglyceride.

Working with DNA (24.4)

71. The genetic code is a triplet code, that is, a sequence of three bases in RNA codes for each amino acid in a peptide chain or protein. How many RNA bases are required to code for a protein that contains 577 amino acids?

72. It has been calculated that the average length of a base pair in a DNA double helix is 3.4 Å. The human genome (the complete set of all DNA in the nucleus of a human cell) contains about three billion base pairs of DNA. In centimeters, how long is the DNA in the human genome? Assume that the DNA is stretched out and not coiled around proteins as it actually is in a living cell. ($1\ \text{Å} = 10^{-10}$ m)

73. A cell of the bacterium *Escherichia coli* has about 4.2×10^6 base pairs of DNA, whereas each human cell has about 3×10^9 base pairs of DNA. What percentage of the size of the human genome does the *E. coli* DNA represent?

Energy Calculations (24.5)

74. Every mole of glucose that undergoes alcoholic fermentation in yeast results in the net synthesis of two moles of ATP. How much energy in kJ is stored in two moles of ATP? Assume 100% efficiency.

75. How many moles of lactic acid are produced when three moles of glucose undergo fermentation in your muscle cells? Assume 100% completion of the process.

76. The synthesis of one mole of the fatty acid palmitic acid from two-carbon building blocks requires seven moles of ATP. How many kJ of energy are required for the synthesis of one mole of palmitic acid?

77. How many grams of glucose can be oxidized completely by 2.0 L of O_2 gas at STP during cellular respiration?

78. Calculate and compare the total energy in kJ that is converted to ATP during the processes of cellular respiration and fermentation.

Mixed Review

Sharpen your problem-solving skills by answering the following.

79. Draw the carbonyl functional groups present in glucose and fructose. How are the groups similar? How are they different?

80. List the names of the monomers that make up proteins, complex carbohydrates, and nucleic acids.

81. Describe the functions of proteins, carbohydrates, lipids, and nucleic acids in living cells.

82. Write a balanced equation for the hydrolysis of lactose.

83. Write a balanced equation for photosynthesis.

84. Write and balance the equation for cellular respiration.

85. Write a balanced equation for the synthesis of sucrose from glucose and fructose.

Thinking Critically

86. Using Numbers Approximately 38 moles of ATP are formed when glucose is completely oxidized during cellular respiration. If the heat of combustion for 1 mole of glucose is 2.82×10^3 kJ/mol and each mole of ATP stores 30.5 kJ of energy, what is the efficiency of cellular respiration in terms of the percentage of available energy that is stored in the chemical bonds of ATP?

87. Recognizing Cause and Effect Some diets suggest severely restricting the intake of lipids. Why is it not a good idea to eliminate all lipids from the diet?

88. Making and Using Graphs A number of saturated fatty acids and values for some of their physical properties are listed in **Table 24-2**.

a. Make a graph plotting number of carbon atoms versus melting point.

b. Graph the number of carbon atoms versus density.

c. Draw conclusions about the relationships between the number of carbon atoms in a saturated fatty acid and its density and melting point values.

d. Predict the approximate melting point of a saturated fatty acid that has 24 carbon atoms.

Table 24-2

Physical Properties of Saturated Fatty Acids

Name	Number of carbon atoms	Melting point (°C)	Density (g/mL) (values at 60–80°C)
Palmitic acid	16	63	0.853
Myristic acid	14	58	0.862
Arachidic acid	20	77	0.824
Caprylic acid	8	16	0.910
Docosanoic acid	22	80	0.822
Stearic acid	18	70	0.847
Lauric acid	12	44	0.868

Writing in Chemistry

89. Write a set of instructions that could be included in a package of contact-lens cleaning solution containing an enzyme. This enzyme catalyzes the breakdown of protein residues that adhere to the lenses. Include information about the structure and function of enzymes and the care that must be taken to avoid their denaturation during use.

90. Use the library or the Internet to research cholesterol. Where is this molecule used in your body? What is its function? Why is too much dietary cholesterol considered to be bad for you?

Cumulative Review

Refresh your understanding of previous chapters by answering the following.

91. a. Write the balanced equation for the synthesis of ethanol from ethene and water.

b. If 448 L of ethene gas reacts with excess water at STP, how many grams of ethanol will be produced? (Chapter 14)

92. Identify whether each of the reactants in these reactions is acting as an acid or a base. (Chapter 19)

a. $HBr + H_2O \rightarrow H_3O^+ + Br^-$

b. $NH_3 + HCOOH \rightarrow NH_4^+ + HCOO^-$

c. $HCO_3^- + H_2O \rightarrow CO_3^- + H_3O^+$

93. What is a voltaic cell? (Chapter 21)

Use these questions and the test-taking tip to prepare for your standardized test.

1. Which of the following is NOT true of carbohydrates?

a. Monosaccharides in aqueous solutions interconvert continuously between an open-chain structure and a cyclic structure.
b. The monosaccharides in starch are linked together by the same kind of bond that links the monosaccharides in lactose.
c. All carbohydrates have the general chemical formula $C_n(H_2O)_n$.
d. Cellulose, made only by plants, is easily digestible by humans.

2. All of the following are differences between RNA and DNA EXCEPT _____ .

a. DNA contains the sugar deoxyribose, while RNA contains the sugar ribose
b. RNA contains the nitrogen base uracil, while DNA does not
c. RNA is usually single-stranded, while DNA is usually double-stranded
d. DNA contains the nitrogen base adenine, while RNA does not

3. Cellular respiration produces about 38 moles of ATP for every mole of glucose consumed:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6CO_2 + 6H_2O + 38ATP$$

If each molecule of ATP can release 30.5 kJ of energy, how much energy can be obtained from a candy bar containing 130 g of glucose?

a. 27.4 kJ
b. 836 kJ
c. 1159 kJ
d. 3970 kJ

4. The sequence of bases in RNA determines the sequence of amino acids in a protein. Three bases code for a single amino acid; for example, CAG is the code for glutamine. Therefore, a strand of RNA 2.73×10^4 bases long codes for a protein that has _____ .

a. 8.19×10^4 amino acids
b. 9.10×10^3 amino acids
c. 2.73×10^4 amino acids
d. 4.55×10^3 amino acids

THE PRINCETON REVIEW **Test-Taking Tip**

Use The Process of Elimination On any multiple-choice test, there are two ways to find the correct answer to each question. Either you can choose the right answer immediately or you can eliminate the answers that you know are wrong.

5. The equation for the alcoholic fermentation of glucose is shown below:

$$C_6H_{12}O_6 \rightarrow 2CH_3CH_2OH + 6CO_2 + \text{energy}$$

The ethanol content of wine is about 12%. Therefore, in every 100 g of wine there are 12.0 g of ethanol. How many grams of glucose were catabolized to produce these 12.0 g of ethanol?

a. 23.4 g
b. 12.0 g
c. 47.0 g
d. 27.0 g

Analyzing Tables Use the table below to answer the following questions.

<u>Note:</u> # of X = # of molecules of X in one DNA molecule

$$\%X = \frac{\text{\# of X}}{\text{\# of A + \# of G + \# of C + \# of T}}$$

where X is any nitrogen base

6. What is the %T of DNA D?

a. 28.4%
b. 78.4%
c. 71.6%
d. 21.6%

7. Every nitrogen base found in a DNA molecule is part of a nucleotide of that molecule. The A nucleotide, C nucleotide, G nucleotide, and T nucleotide have molar masses of 347.22 g/mol, 323.20 g/mol, 363.23 g/mol, and 338.21 g/mol respectively. What is the mass of one mole of DNA A?

a. 2.79×10^5 g
b. 2.7001×10^5 g
c. 2.6390×10^5 g
d. 2.72×10^5 g

8. How many molecules of adenine are in one molecule of DNA B?

a. 402
b. 434
c. 216
d. 175

Nitrogen Base Data for Four Different Double-Stranded DNA Molecules

DNA Molecule	# of A	# of G	# of C	# of T	%A	%G	%C	%T
A	165	?	231	?	20.8	?	29.2	?
B	?	402	?	?	?	32.5	?	?
C	?	?	194	234	?	?	22.7	27.3
D	266	203	?	?	28.4	21.6	?	?